UNIV. OF
TORONTO
LIBRARY

BINDING LIST [illegible] 1 5 1924

Digitized by the Internet Archive
in 2010 with funding from
University of Toronto

http://www.archive.org/details/proceedings61inst

LIBRARY
JAN 30 [illegible]

Technol

# THE JOURNAL OF

# The Institution of Electrical Engineers

ORIGINALLY

The Society of Telegraph Engineers

FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

EDITED BY P. F. ROWELL, SECRETARY.

SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C. 2.

VOL. 61, 1923.

188175
4.3.24

E. AND F. N. SPON, LIMITED, 57, HAYMARKET, LONDON, S.W. 1
SPON AND CHAMBERLAIN, 123, LIBERTY STREET, NEW YORK
1923

# The Institution of Electrical Engineers.

VICTORIA EMBANKMENT, LONDON, W.C. 2.

FOUNDED 1871.
INCORPORATED BY ROYAL CHARTER 1921.

---

Patron: HIS MAJESTY KING GEORGE V

---

## COUNCIL, 1922-1923.

### President.

F. GILL, O.B.E.

### Past-Presidents.

TK
1
I4
v.61

ALEXANDER SIEMENS.—1894 & 1904.
COLONEL R. E. CROMPTON, C.B.—1895 & 1908.
SIR HENRY MANCE, LL.D., C.I.E.—1897.
JAMES SWINBURNE, F.R.S.—1902.
SIR R. T. GLAZEBROOK, K.C.B., D.Sc., F.R.S.—1906.
W. M. MORDEY.—1908.
DR. S. Z. DE FERRANTI.—1910 & 1911.
SIR JOHN SNELL.—1914.
CHARLES P. SPARKS, C.B.E.—1915 & 1916.
C. H. WORDINGHAM, C.B.E.—1917 & 1918.
ROGER T. SMITH.—1919.
LL. B. ATKINSON.—1920.
J. S. HIGHFIELD.—1921.

### Vice-Presidents.

W. H. ECCLES, D.Sc., F.R.S.
PROF. E. W. MARCHANT, D.Sc.
C. C. PATERSON, O.B.E.
A. A. C. SWINTON, F.R.S.

**Honorary Treasurer.**—SIR JAMES DEVONSHIRE, K.B.E.

### Ordinary Members of Council.

J. W. BEAUCHAMP.
R. A. CHATTOCK.
F. W. CRAWTER.
D. N. DUNLOP.
K. EDGCUMBE.
S. EVERSHED.
A. F. HARMER.
P. V. HUNTER, C.B.E.
LT.-COL. F. A. CORTEZ LEIGH, T.D., R.E.
A. H. W. MARSHALL.
SIR WILLIAM NOBLE.
SIR ANDREW M. OGILVIE, K.B.E., C.B.
A. PAGE.
W. R. RAWLINGS.
T. ROLES.
A. RUSSELL, D.Sc.
A. W. TAIT, C.B.E.
C. VERNIER.

### Chairmen and Past-Chairmen of Local Centres.

F. G. C. BALDWIN (*North-Eastern*).
A. S. BARNARD (*North-Western*).
*W. E. BURNAND (*North Midland*).
*R. A. CHATTOCK (*South Midland*).
PROF. W. CRAMP, D.Sc. (*South Midland*).
*R. N. EATON (*Irish*).
*E. T. GOSLIN (*Scottish*).
A. S. HAMPTON (*Scottish*).
E. C. HANDCOCK (*Irish*).
*A. C. MACWHIRTER (*Western*).
*PROF. W. M. THORNTON, O.B.E., D.Sc. (*North-Eastern*).
F. TREMAIN (*Western*).
*W. WALKER (*North-Western*).
G. E. F. WEBBER (*Argentina*).
B. WELBOURN (*Mersey and North Wales*).
*J. WILSON (*Argentina*).
W. B. WOODHOUSE (*North Midland*).

* Past-Chairmen.

---

### Auditors.

ALLEN, ATTFIELD & Co.,
CLARENCE HOUSE, 24, MARTIN LANE, E.C. 4.

### Solicitors.

BRISTOWS, COOKE & CARPMAEL,
1, COPTHALL BUILDINGS, E.C. 2.

### Secretary.

P. F. ROWELL.

The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.

# TABLE OF CONTENTS.

## Vol. 61, 1923.

Portrait of Mr. F. Gill, President .. *Frontispiece*

PAGE

**Inaugural Address** by the President (F. Gill) .. 1

**Address** by F. Tremain, Chairman of the Western Centre 16

**Address** by R. D. Archibald, Chairman of the Dundee Sub-Centre .. .. .. .. .. .. 21

**Address** by F. G. C. Baldwin, Chairman of the North-Eastern Centre .. .. .. .. .. 24

**Address** by B. Welbourn, Chairman of the Liverpool Sub-Centre .. .. .. .. .. .. .. 31

**Address** by W. B. Woodhouse, Chairman of the North Midland Centre .. .. .. .. .. 35

**Address** by W. Pearson, Chairman of the East Midland Sub-Centre .. .. .. .. .. .. .. 37

**"The Production of Noise and Vibration by Certain Squirrel-Cage Induction Motors."** By F. T. Chapman, D.Sc. .. .. .. .. .. .. .. 39

**"An Electrical Timing Device for Short Intervals."** By Professor D. Robertson, D.Sc., and N. F. Frome, B.Sc. .. .. .. .. .. .. .. 49

**"The Engineer and Manufacturing Costs."** By F. C. Lawrence, M.C., B.Sc.Tech. .. .. .. 52

**"The Testing of Materials used in the Manufacture of Electrical Equipment."** By C. Dawson .. .. 59

**"Observations of the Field Strength of Horsea Wireless Station."** By E. B. Moullin, M.A. .. .. 67

Discussion .. .. .. .. .. .. .. 308

**"Telephonic Repeaters and Long-Distance Telephony."** By J. A. Cooper .. .. .. .. .. .. 75

**"Automatic and Semi-Automatic Railway Signalling."** By H. S. Petch, B.Sc. .. .. .. .. .. 81

**"The Improvement of Power Factor."** By the late Dr. G. Kapp .. .. .. .. .. .. .. 89

Discussion :
- Before the Institution .. .. .. .. 109
- ,, North-Eastern Centre .. .. .. 116
- ,, North Midland Centre .. .. .. 119
- ,, Liverpool Sub-Centre .. .. .. 124
- ,, North-Western Centre .. .. .. 130
- ,, Western Centre .. .. .. .. 896
- ,, Scottish Centre .. .. .. .. 899

**Address** by Professor W. Cramp, D.Sc., Chairman of the South Midland Centre .. .. .. .. 136

**Address** by E. C. Handcock, Chairman of the Irish Centre .. .. .. .. .. .. .. 141

**Address** by A. S. Barnard, Chairman of the North-Western Centre .. .. .. .. .. 145

**Address** by A. S. Hampton, Chairman of the Scottish Centre .. .. .. .. .. .. .. 149

**Address** by H. West, Chairman of the Sheffield Sub-Centre .. .. .. .. .. .. .. 152

**Address** by W. P. Richmond, Chairman of the Tees-Side Sub-Centre .. .. .. .. .. 157

**"The Measurement of Flux Density in the Air Path of a Magnetic Circuit."** By W. P. Conly, B.Sc. .. 161

**"Electricity as applied to Mines."** By J. C. Stewart 167

**"Hydro-Electric Power Supply."** By A. Tustin, M.Sc. 174

**"The Effect of Local Conditions on Radio Direction-Finding Installations."** By R. L. Smith-Rose, M.Sc., and R. H. Barfield, B.Sc. .. .. .. 179

Discussion before the Wireless Section .. .. 191

**"Domestic Load Building : A Few Suggestions upon Propaganda Work."** By W. A. Gillott .. .. 197

Discussion :
- Before the Institution .. .. .. .. 202
- ,, North-Eastern Centre .. .. .. 206
- ,, Liverpool Sub-Centre .. .. .. 209
- ,, North Midland Centre .. .. .. 214
- ,, Scottish Centre .. .. .. .. 392
- ,, Western Centre .. .. .. .. 890

**"The Possibilities of Transmission by Underground Cables at 100 000/150 000 Volts."** By A. M. Taylor 220

Discussion :
- Before the Institution .. .. .. .. 239
- ,, North-Eastern Centre .. .. .. 248
- ,, South Midland Centre .. .. .. 250
- ,, Scottish Centre .. .. .. .. 382
- ,, Mersey and North Wales (Liverpool) Centre .. .. .. .. .. 385

**"Electric Arc Welding Apparatus and Equipment."** By J. Caldwell .. .. .. .. .. .. 253

Discussion before the Institution .. .. .. 268

**Address to the London Students' Section,** by C. H. Wordingham, C.B.E. .. .. .. .. .. 277

**Address to the Scottish Students' Section,** by J. F. Nielson .. .. .. .. .. .. .. .. 280

**"The Operation of Induction Motors in Cascade."** By H. Cotton, M.B.E., M.Sc. .. .. .. .. 284

PAGE

**"A Direct-Reading Thermionic Voltmeter, and its Applications."** By E. B. Moullin, M.A. .. .. 295
Discussion before the Wireless Section .. .. 304

**"Variable-Speed Alternating-Current Motors without Commutators."** By F. Creedy .. .. .. 309
Discussion :
Before the Institution .. .. .. .. 326
,, North Midland Centre .. .. .. 330
,, South Midland Centre .. .. .. 330
,, North-Eastern Centre .. .. .. 332
,, Western Centre .. .. .. .. 960

**"Works Production."** By G. H. Nelson .. .. 338
Discussion :
Before the Institution .. .. .. .. 352
,, North-Western Centre .. .. .. 358
,, North-Eastern Centre .. .. .. 893

**"The Rating of Cables for Intermittent or Fluctuating Loads."** By S. W. Melsom and H. C. Booth .. 363

**"American Practice as regards the Generation of Suitable Voltages and Currents for Deep Therapy."** By C. H. Holbeach .. .. .. .. .. .. 369

**"An Apparatus for demonstrating the Magnetomotive Forces produced by Single-Phase and Polyphase Windings."** By R. D. Archibald .. .. .. 376

Discussion on **"The Properties of the Distribution Factor of Armature Windings"** .. .. .. 398

**"Stationary Waves on Open-Ended Solenoids."** By A. Press .. .. .. .. .. .. .. 405

**"The Design of Radio Towers and Masts: Wind-Pressure Assumptions."** By C. F. Elwell .. 407
Discussion before the Wireless Section .. .. 412

**"The Maintenance of Voltage on a D.C. Distribution System by means of a Fully Automatic Substation."** By P. J. Robinson .. .. .. .. .. .. 417
Discussion :
Before the Institution .. .. .. .. 425
,, North Midland Centre .. .. .. 428
,, North-Eastern Centre .. .. .. 430
,, Mersey and North Wales (Liverpool) Centre .. .. .. .. .. 433
,, South Midland Centre .. .. .. 435
,, North-Western Centre .. .. .. 704
,, Scottish Centre .. .. .. .. 709

**"Some Problems in High-Speed Alternators, and their Solution."** By J. Rosen .. .. .. .. 439
Discussion :
Before the Institution .. .. .. .. 458
,, Scottish Centre .. .. .. .. 468
,, North Midland Centre .. .. .. 473
,, Western Centre .. .. .. .. 869
,, North-Eastern Centre .. .. .. 874
,, North-Western Centre .. .. .. 876
,, East Midland Sub-Centre .. .. 884
,, South Midland Centre .. .. .. 886

**"The Use of Single-Core Sheathed Cables for Alternating Currents."** By Professor W. Cramp, D.Sc., and Nora I. Calderwood, M.A., B.Sc. .. .. .. 477

**"Directions for the Study of Pressboard for Electrical Insulating Purposes."** .. .. .. .. .. 486

PAGE

Discussion before the Western Centre on **"The Interconnection of Alternating-Current Power Stations"** 496

**"The Measurement of the Electric Intensity of Received Radio Signals."** By J. Hollingworth, M.A., B.Sc. 501
Discussion before the Wireless Section .. .. 510

**"Permissible Current Loading of British Standard Impregnated Paper-Insulated Electric Cables"** .. 517
Discussion :
Before the Institution .. .. .. .. 579
,, North-Eastern Centre .. .. .. 586
,, North Midland Centre .. .. .. 587
,, North-Western Centre .. .. .. 590
,, South Midland Centre .. .. .. 592
Authors' reply .. .. .. .. .. .. 944

**"Problems in Telephony, Solved and Unsolved."** (The Fourteenth Kelvin Lecture.) By Professor J. A. Fleming, M.A., D.Sc., F.R.S. .. .. .. 613

**"Permanent Magnets, and the Relation of their Properties to the Constitution of Magnet Steels."** By E. A. Watson .. .. .. .. .. .. 641

**Report on Researches on the Chemical and Physical Properties of Insulating Oils** .. .. .. 661

**"Power Factor: its Technical and Commercial Aspects."** By H. E. Yerbury .. .. .. .. .. 675
Discussion :
Before the Sheffield Sub-Centre .. .. .. 681
,, North Midland Centre .. .. .. 688

**"The Pulling into Step of an Induction-Type Synchronous Motor."** By L. H. A. Carr, M.Sc.Tech. .. .. 692

**"A Bridge Method for determining Dielectric Losses at Wireless Frequencies."** By M. D. Hart, M.Sc... 697

**"A Physical Phenomenon and its Applications to Telegraphy, Telephony, etc."** By A. Johnsen and K. Rahbek .. .. .. .. .. .. 713

**"Co-operation between the Architect and the Electrical Engineer."** By F. Hooper, F.R.I.B.A. .. .. 726

**"Co-operation between the Architect and the Electrical Engineer."** By J. W. Beauchamp .. .. 728

Discussion on the above papers by Mr. F. Hooper and Mr. J. W. Beauchamp at a Joint Meeting of The Institution and the Royal Institute of British Architects .. .. .. .. .. .. .. 736

**"A Mathematical Development of the Theory of the Magnetomotive Force of Windings."** By A. E. Clayton, D.Sc.(Eng.) .. .. .. .. .. 749

**Address to the London Students' Section,** by F. Gill .. 788

**"Induction Motors used as Synchronous Machines."** By S. V. Ganapati and R. G. Parikh, B.Sc. .. 795

**"Directional Wireless Telegraphy in Aircraft."** By C. K. Chandler, M.B.E. .. .. .. .. .. 803

**"Transoceanic Wireless Telephony."** By Dr. H. W. Nichols .. .. .. .. .. .. .. 812
Discussion before the Institution .. .. .. 820

**"An Electrode Apparatus for the Location of Submarine Cables and Faults."** By F. B. Young, B.A., D.Sc., and W. Jevons, M.Sc., A.R.C.S. .. .. .. .. 822

PAGE

"**The Drive of Power Station Auxiliaries.**" By L. Breach and H. Midgley, B.Sc.(Eng.) .. .. 829
Discussion :
  Before the Institution .. .. .. .. 845
  ,, Mersey and North Wales (Liverpool) Centre .. .. .. .. 851
  ,, Scottish Centre .. .. .. .. 858
"**The Compound Characteristic in Regenerative Braking with Direct-Current Traction.**" By M. G. Say, M.Sc., and H. G. Frampton .. .. .. 863
"**The Application of a Revolving Magnetic Drum to Electric Relays, Siphon Recorders and Radio Transmitting Keys.**" By N. W. McLachlan, D.Sc.(Eng.) .. .. .. .. .. .. .. 903
Discussion before the Wireless Section .. .. 926
"**The Design of Inductances for High-Frequency Circuits.**" By Professor C. L. Fortescue .. .. 933
Discussion before the Wireless Section .. .. 939
"**The X-Ray Examination of Materials.**" By A. G. Warren, M.Sc. .. .. .. .. .. .. .. 949
"**Directions for the Study of Vulcanized Fibre for Electrical Purposes**" .. .. .. .. 964
"**Directions for the Study of Electrical Insulating Papers (Unvarnished) for Purposes other than the Manufacture of Cables**" .. .. .. .. .. 982
"**Report upon Tests on Hard Drawn Copper Wires and Cables for Overhead Transmission Lines**" .. 997
"**Report upon Tests on Hard Drawn Aluminium Wires and Cables for Overhead Transmission Lines**" .. 1013
"**Report upon Tests on Galvanized Steel Wires and Cables for Overhead Transmission Lines** .. .. 1026
"**Report upon Tests on Steel-Cored Aluminium Cables for Overhead Transmission Lines**" .. .. 1041
"**Electric Line Calculations : their Practical Application to Transmission and Distribution Problems**" By W. T. J. Atkins, B.Sc.(Eng.) .. .. .. 1044
"**Wireless Direction-Finding in Steel Ships.**" By C. E. Horton .. .. .. .. .. .. .. .. 1049
Discussion before the Wireless Section .. .. 1056

PAGE

"**The Calculation of Air-Space Flux.**" By Professor W. Cramp, D.Sc., and Nora I. Calderwood, M.A., B.Sc. .. .. .. .. .. .. .. 1061
"**The Leakage Flux between Parallel Pole-Cores of Circular Cross-Section.**" By B. Hague, M.Sc. .. 1072
"**The Effect of Shearing Stress on the Span Calculations of a Suspended Cable.**" By Professor T. Ohtsuki 1079
"**The Nature of the Magnetic Field produced by the Stator of a Three-Phase Induction Motor, with special reference to Pole-Changing Motors.**" By F. J. Teago .. .. .. .. .. .. .. 1087
"**Wind-driven Generators.**" By W. Stirling .. .. 1096
"**The Electric Battery Vehicle.**" By H. E. Dance .. 1100
"**Steam Turbine Blading.**" By J. C. Read, B.Sc. .. 1109
"**Temperature Measurement with the Einthoven Galvanometer.**" By F. Adcock, Ph.D., and E. H. Wells, Ph.D. .. .. .. .. .. .. 1115
"**The Theory of the Generation of Alternating Currents by means of Triodes.**" By N. Shuttleworth, M.Sc. 1121
"**Experiments on Modes of Resonant Vibrations of Telephone Receiver Diaphragms.**" By Professor J. T. MacGregor-Morris and Professor E. Mallett, M.Sc.(Eng.) .. .. .. .. .. .. .. 1134
Annual Accounts for 1922 .. .. .. .. 604
Annual Dinner, 1923 .. .. .. .. .. 400
Annual General Meeting .. .. .. .. .. 1146
Benevolent Fund Accounts for 1922 .. .. .. 703
Benevolent Fund, Annual General Meeting and Report of Committee .. .. .. .. .. .. .. 702
Obituary Notices .. .. .. .. .. .. 1151
Proceedings of the Institution 64, 293, 403, 610, 700, 800, 1139
Report of the Council for the year 1922-23 .. .. 594
Special General Meeting of 19 July, 1923 .. .. 1150
Index .. .. .. .. .. .. .. 1161

## CORRIGENDA TO VOL. 61.

Page 44, col. 2, second line from bottom : *For* " (13) " *read* " (10)."

Page 45, col. 1, line 2 : *For* " (14) " *read* " (11)."

Page 45, col. 1, line 15 : *For* " $(n - m)$ " *read* " $(m - n)$."

Page 245, col. 2, line 34 : *For* " $4X \times \frac{0 \cdot 1}{0 \cdot 150}$ " *read* " $4X \times \frac{0 \cdot 185}{0 \cdot 150}$ "

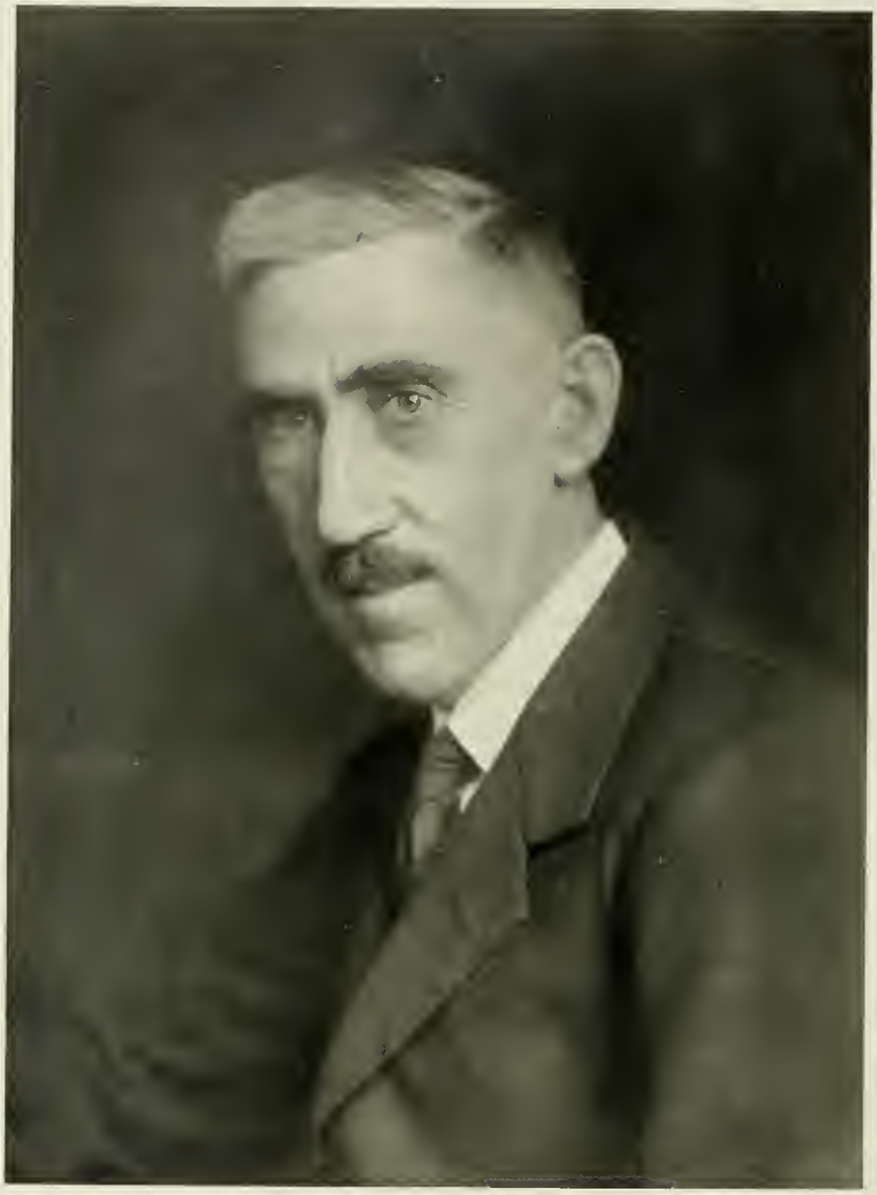
Page 247, col. 2, line 45 : *For* " 100 000-kW " *read* " 200 000-kW."

Page 247, col. 2, line 47 : *For* " £0·18 " *read* " £0·10."

Page 247, col. 2, line 50 : *For* " £0·2 " *read* " £0·1."

Pages 517–579. Corrections to the paper on "Permissible Current Loading of British Standard Impregnated Paper-Insulated Electric Cables" will be found on page 918.

Page 792, col. 1, ninth line from bottom : *For* " $\overset{£}{15}\ \overset{s.}{15}\ \overset{d.}{0}$ " *read* " $\overset{£}{25}\ \overset{s.}{0}\ \overset{d.}{0}$."



J. Gill.

PRESIDENT 1922-1923

Elliott & Fry, Ltd., photo.

Emery Walker Ltd., ph. sc.

THE JOURNAL OF
The Institution of Electrical Engineers
**VOL. 61.**

# INAUGURAL ADDRESS

By FRANK GILL, O.B.E., President.

(*Address delivered before* THE INSTITUTION, 2*nd November*, 1922.)

## THE INSTITUTION.

My first duty must be to express my thanks to the members of this great Institution for their confidence in placing me in this chair, in the past successfully occupied by many eminent men; and as representing, in some degree, electrical engineers who have devoted their energies to what may be termed the light side of the science, I thank you for your trust. I confess to a feeling, not so much of pride in taking this office, as of doubt whether one can properly fill the position. Fortunately, I have no responsibility for the election—that is yours—but on me devolves the duty of doing the utmost of which I am capable to serve the Institution. That by itself, however, is not enough; the President is merely the spear point or the tool face, and that which may be accomplished by the point depends largely on the body behind it. By itself it can do little. I know your President is always assured of the support and sympathy of your Council, but I ask more—it is necessary that the living interest and support of every member should be behind the Council in their labours on your behalf.

As you are aware, the Institution is in point of numbers now the largest engineering Society in the British Empire, the total membership at the commencement of this session being 10 461 and the increase during the past twelve months 867. The conditions of, and qualifications for, membership are not being eased in any way, but are rather being made more severe; membership is becoming more recognized as a qualification, and the Royal Charter gives an added dignity and prestige. I want to see, and do not hesitate to call for, ungrudging service to the Institution from all its members, certain that if each will actively realize that the Institution is *his* Institution, its powers of, and opportunities for, useful service to mankind will be greatly enlarged. One of the grandest things about the engineering profession is its splendid tradition of service regardless of the cost to the server, fitly illustrated by the death of those to whose immortal memory the panels in the hall of this building stand, reminding all who enter of the simple road to greatness—Whosoever will be chief among you let him be your servant.

## TECHNICAL EDUCATION.

As one illustration of service, the new Technical Education Scheme may be mentioned. You are aware from the Council's Report last May that the Board of Education has sought the assistance of the Institution in its management of technical education in England and Wales; accordingly, a joint Committee, on which the Board of Education and this Institution are equally represented, will be responsible for the curriculum in Electrical Engineering at such schools as elect to join in the scheme, for certifying as to the satisfactory nature of the schools and for the final examinations; and the certificates and diplomas issued to successful candidates will be signed on behalf of the Institution, the Board of Education, and the school. Many of our members feel strongly on the question of Education, and some have criticized the existing state of affairs in writings and verbally; now is their opportunity. Apart from service on the joint Committee, cases will certainly arise where they can help by showing interest in those schools which adopt the scheme, by gifts of apparatus and plant, by facilitating visits of students to works, by finding work for the students, and by criticism of the course of training, so as to make it really adapted for turning out men best equipped for their work in the world.

I want to make a special appeal also of a somewhat similar nature for interest in the work of the schools. It is tremendously important that, during their course of study, students should get first-hand acquaintance with actual commercial conditions, both as regards the conditions of work and acquaintance with the workers. So we find that universities and colleges endeavour to get temporary practical work for their students during vacations or at other times. It seems to me that managers (it is becoming an anachronism to speak of "employers") ought to feel it a duty to make temporary vacancies for such students, realizing that as hereinafter they will require adequately trained men from the schools, so in the meantime they also must do their share in the educational scheme by providing facilities impossible to the schools but possible to industry. As the time for premium pupils has, or ought to have, passed away, so the time for hesitation in taking in such men for short periods ought also to pass away. Let the managers regard the students as possible future workers, and demand from them qualifications for apprehending what they see. I make a very earnest appeal to all those members of the Institution who are in positions enabling them to influence either opinion or practice on this matter, to make a point of doing what they can to meet this need. We take great care in the selection and treatment of the raw material to be worked up ; we do not always take sufficient pains in selecting and training the raw human personnel which is to be trusted with the working of the raw material.

With great diffidence may I also say a word to those in control of the schools. During my time I have had a considerable number of men direct from the universities and colleges, among them, I am glad to say, being some very brilliant engineers, and I do not recollect a single failure. Probably the method of selection, in which great weight is attached to the opinion of the professor as to the character of the applicant, has had a good deal to do with the success experienced. But I do not remember an instance of a student being familiar with the economic aspect of engineering studies, nor of one who had any idea of how to tackle a problem of engineering economics. Yet that question of economics is the fundamental problem of the engineer ; let him neglect it and, even though brilliant, he becomes something else, a physicist perhaps, a mechanician or a constructor, but not an engineer, who, it seems to me, must ever link together the progress of science with the minimum of human effort, that is, with the most economical manner of achieving what is desired. In the construction of plant how often it happens that, when the engineer has decided what plant shall be installed, the question as to whether the plant shall or shall not be profitable is also decided ; for when the plant has been constructed to the engineer's designs, the management can only affect results by a margin, important no doubt, but the fact remains that the decision as to what plant shall be installed settles also many other items of expense, both for labour and material. I know that the time at the schools is very fully occupied, but I believe that this subject of engineering economics ought not to be left untouched.

## Electrical Communication.

I have thought that the subject to which I could most usefully direct your attention is one relating to the art of Electrical Communication, and particularly, though not exclusively, to Telephony over Considerable Distances. I propose, therefore, briefly to review some of the recent advances in the telephone art which affect long-distance communication in Europe, or, as I prefer to call it, " through communication," because distance is not necessarily a feature, though often it is present.

If we consider primitive man, his first and immediate need is for food, then shelter and defence, then tools and clothes ; but directly he has arrived at the state in which his own and his immediate neighbours' wants have been supplied, so far as their own exertions can supply them, the need for communication arises, and that even before the need for transportation. There is, however, no need to insist on any priority as between these two arts. They are so intimately connected that we may, without any violence to meaning, define communication as transportation of intelligence. Without communication man cannot know where to obtain such of his requirements as he himself is unable to satisfy ; without it there is no use in his producing more than he requires for himself, since, in its absence, he cannot know whence arises a demand for his spare produce. While all this is true of primitive man, it has applied much more intensely since machinery came to the aid of production in the complicated system of trade which now serves the world. That which fifty years ago was regarded as a luxury to be enjoyed only by the few, is now a necessity to the many ; to-day no nation stands alone or is sufficient for itself ; more and more the interdependence of nations is being recognized ; and more and more is it realized that no nation can be prosperous or afflicted without a result being felt by other nations. It were easy to illustrate this community of nations by taking the clothes we wear, the food we eat ; but all this is well known to you. It is sufficient to say that to bring together the products of all the world to your doors is the work of communication and transportation, and that the efficiency of both is vital. Other things being equal, the nation best equipped with the means of production, communication and transportation, will enjoy a great advantage in the race for commercial supremacy, and perhaps also in the search after national well-being. It follows, therefore, that a great responsibility is laid on those to whom is entrusted the means of communication, or who control those means, whether Government department, public company or other agency, and particularly so because it is at last generally recognized that competition is not an aid to efficiency in this business. In return, therefore, for the grant of facilities to carry on its work, each grantee authority must ultimately recognize its duty to the public and, if it realizes this, dare not adopt either the selfish attitude of attempting to make as much profit as possible, or the passive attitude of merely supplying the service demanded by the public. To discharge its duty it must diligently and actively search out new means and facilities and also set about educating the public in regard to their need for communication. The authority is the custodian of the knowledge ; it must teach the public what the public did not at first realize—that efficient communication is the life blood of commerce and of national and international understanding and amity—and without effective communication there would appear to be little chance of success for such projects as the League of Nations. It is by this campaign of education that the well-developed industries of the world have been stimulated, not by merely diligently serving the public demand. The railways have themselves created demands for traffic, the Press has done the same, so has every great and successful industry, and so must the telephone industry if it is not to fail in the performance of its duty.

The fact that so much of the means of electrical communication in Europe is under Government ownership, and under the present prevailing custom removed from the stimulus of profit-earning, makes it quite possible that Governments may instruct their Telephone and Telegraph Departments that they do their duty when they diligently supply the public demands for service; and perhaps such a course is the more probable when the many other calls for expenditure experienced by Governments to-day are considered. But here a deliberate choice must be made: Is communication, and ever better communication, a necessity or not? If it is, then the passive attitude of merely satisfying public demands must be abandoned and an aggressive attitude take its place. It is not by a passive attitude that the great development in telephones has been built up in the United States, Canada, Denmark, Sweden and Norway, but rather by a resolute, purposeful and well-directed campaign of education of the public and of existing users. In the United States particularly there has for years been an educational campaign of a very high order, coupled with the construction of plant in advance, without which it is, of course, worse than useless to create demand. All this seems self-evident and trite, but two questions will test very quickly whether in fact this matter is quite so self-evident and obvious as it appears. These questions are: (1) Has telephony, during the 46 years it has been available, been of as much use to Europe as it might have been? (2) Have the organizations, Government and otherwise, been permitted to do what they have wished to do? The answer to both questions is most decidedly—No!

It will be noticed that above it was assumed, for the moment, that lack of profit-earning robbed a Government of the stimulus enjoyed by a public company; also that a Government department should not earn any more money than necessary to be self-supporting. It seems to me that both assumptions are fallacious. It is true, of course, that with a company the necessity for earning an adequate return on investment is a most rigorous stimulus, but, apart from profit-earning, a Government is subject to a powerful stimulus also. Only let it be realized that communication means something real—that it is a tool for the benefit of the nation, a necessity—and who is more vitally interested in obtaining the fullest possible utilization of that necessity than a Government? Who more vitally interested or more impelled to strain every nerve to teach the public the advantages of communication and extend the use of it by every means possible? The stimulus of profit-earning to produce development is small compared with the stimulus which comes to a public department as trustee for the nation.

But it seems also wrong to reason that a Government department should not earn something more than just enough merely to pay its way. It is undoubtedly healthy for the *esprit de corps* of any organization that its personnel should know that their organization is an efficient one, in which they can take a justifiable pride; and one of the ways of testing the efficiency of public concerns is to associate service with returns. With a staff comprising many persons, it is unhealthy that the idea should prevail that profit-earning is of no account. There is, however, more than the question of the effect on the staff, important though that be. Without a surplus of income over expenses, there is no margin for unforeseen contingencies which must constantly arise in such a flexible business; service trials and research are likely to be adversely acted upon, and capital will be raised with greater difficulty. Further, there seems no reason why a Government should not include in the rentals a sum plainly intended to be a contribution towards revenue; it is difficult to see any reason why it is permissible, for the purpose of raising revenue, to tax, say, food but not telephones, or why it is proper to make a considerable surplus on postage, but not on telephones. It would seem that the correct course is for a Government, if it operates the telephones of a nation, to raise from them something towards the National Revenue, and to pay such a return on the capital invested in the business as to make certain its ability to raise whatever money may be required to extend the business.

Let us now pass on to consider some of the alterations in practice caused by recent developments in telephony as they affect long-distance or through communication.

*Loading.*—By this term is meant the deliberate addition of inductance to the circuit for the purpose of increasing the distance over which satisfactory speech is feasible. Such inductance may be in the form of evenly distributed inductance effected by wrapping the copper conductor with magnetic material, such as fine iron wire, or, and more commonly, may be in the form of lumped inductances obtained by inserting in series in the circuit at intervals coils having the required inductance and a minimum resistance. In was in 1887 that Oliver Heaviside pointed out that the addition of inductance by either of these methods—inductance being then thought harmful—would be beneficial to the transmission of speech.

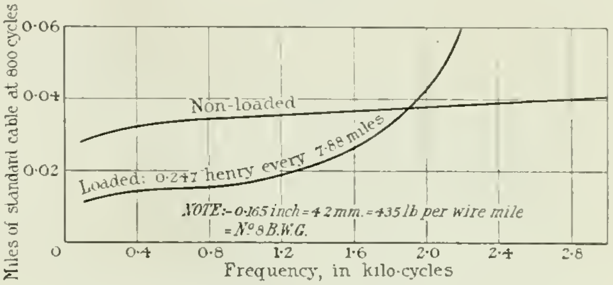


FIG 1.—Attenuation/frequency characteristic of 1 mile of 0·165 inch open wire line. Dry weather conditions assumed.

Fig. 1 shows the loss for one mile of circuit at various frequencies in respect of open wire circuits weighing 435 lb. per mile (4·2 mm diam.) both for non-loaded and for circuits loaded with 0·247 henry every 7·88 miles (12·7 km); the computations are made for the steady state, that is, when the temporary effect of transients has passed off. From these curves we may see that the effect of loading has been threefold: (1) The attenuation has decreased, taking 800 cycles for example, from 0·035 to 0·016 mile of standard cable, a reduction in loss, that is an improvement in volume of speech, of 54 per cent. (2) Between about 400 and 2 000 cycles the curve of loss has a greater slope for the loaded line, indicating that the various frequencies necessary to transmit satisfactory speech are less uniformly transmitted, thus increasing the frequency distortion and so degrading somewhat the quality, which was of a very high order on the non-loaded line. (3) At about 2 000 cycles the attenuation of the loaded line undergoes a decided increase, termed the cut off, so that high frequencies are extinguished. In addition to these three effects the speed of the circuit has fallen from 180 000 miles per second for the nnloaded line to 55 000 miles per second for the loaded line.

Fig. 2 shows the results of loading a circuit weighing 20·6 lb. per mile in dry-core cable with three different types of coil, each at a spacing of 6 000 feet (1 829 m). From this we notice four results: (1) The 800-cycle attenuation has fallen from 0·94 to 0·30 (taking the middle loaded curve as an example), a reduction of 68 per cent in the loss, a greater reduction than was obtained in the case of open wire. (2) Between 200 and 2 000 cycles the loaded curve is approximately horizontal, indicating that all frequencies between those limits are almost equally transmitted, so that the frequency distortion, previously rather high, is made less, while the non-loaded curve has a pronounced slope; for example, the loss at 2 000 cycles is 1·45, that is, 56 per cent greater than at 800 cycles. (3) There is the same cut-off effect as was noticed on open wire lines when loaded. (4) The frequency of the cut-off point also falls as the loading increases. An additional effect is that the speed of the circuit decreases as the loading increases.

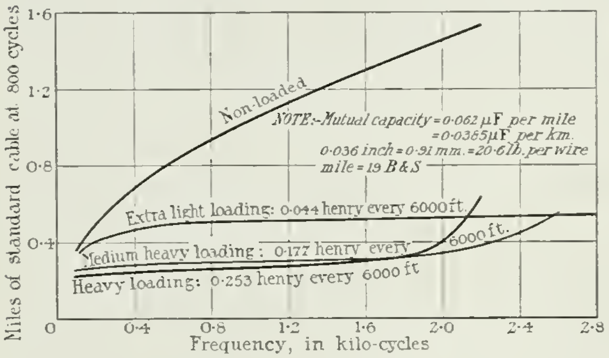


FIG. 2.—Attenuation/frequency characteristic of 1 mile of 0·036 in. cable circuit.

Figs. 3 and 4 show the effect of loading on the cut-off frequency and upon the velocity of the cable circuits referred to in Fig. 2.

It is seen, therefore, that the addition of inductance to circuits, whether open wire or cable, affords a means of greatly extending the distance to which speech is possible, and of reducing the copper required to transmit speech over such distances as were previously feasible. But it is also seen that, while loading reduces frequency distortion on the cable circuit, it increases this form of distortion on the open wire circuit; also that, by increasing the voltage in the circuit, it augments cross-talk, and it reduces the speed of propagation in the circuit.

So far as open lines are concerned, the reactions on the general plant caused by loading are that a higher class of construction, including transposition, and maintenance is required to avoid cross-talk and to keep up the insulation, for loaded lines are much more susceptible to reduction in transmission efficiency due to lowered insulation than are non-loaded lines. With poor maintenance it may well be that the number of days in the year during which the improvement due to loading is gained is not sufficient to pay for the cost of loading.

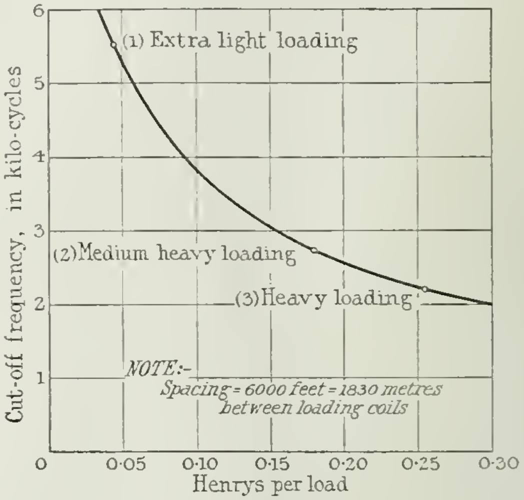


FIG. 3.—Effect of loading upon cut-off frequency.

This condition of constantly maintained high insulation applies also to loaded cable lines, but, high insulation being comparatively easy to achieve in cables, little reaction is caused by this. The increased cross-talk caused by loading has, however, caused real difficulty, which has been overcome by great advances in the cable art, not only as regards the construction of long-distance cable in the factory, but also as regards the jointing of the wires in the field, both these being intended to secure such freedom from unbalance

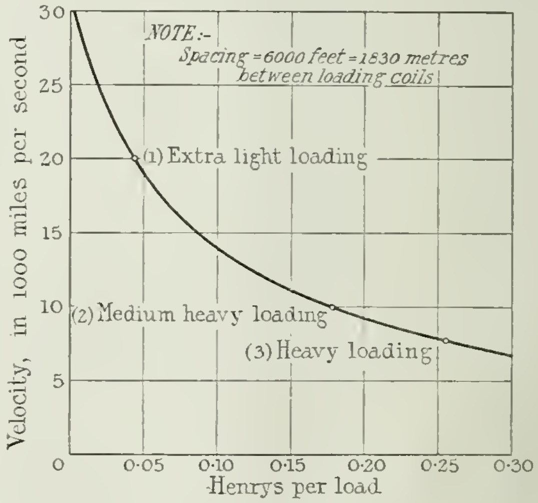


FIG. 4.—Effect of loading upon velocity of propagation.

between circuits as will obviate cross-talk. It must further be noted that here, as in many of the latest developments, the effect of variables is not necessarily local; that is to say, a defect in one place may be felt a long way off in a section where no defect exists. There was also at one time, but this does not now occur so often, a necessity for great care to guard loading coils from becoming magnetized; this has been avoided in cable loading-coils by the use of compressed magnetic dust for the cores.

*Repeaters.*—Although the telephone repeater has been in service since 1905, it is only since 1914 that the thermionic repeater (which followed the introduction of the grid or third element by de Forest into the two-element thermionic valve of Fleming) has been employed, and the great impetus to its use has been given only during the last five years or so. The fact that a three-electrode vacuum tube acts as an amplifier of speech currents has led to an idea that a telephone repeater begins and ends in a device which relays the received current very much as does an electromagnetic relay; but the telephone repeater has many important conditions besides the amplifying one, and the fact that the reactions on telephone practice, due to the advent of the practical telephone repeater, have been and will be of very special importance makes it worth while to devote some little time to their consideration.

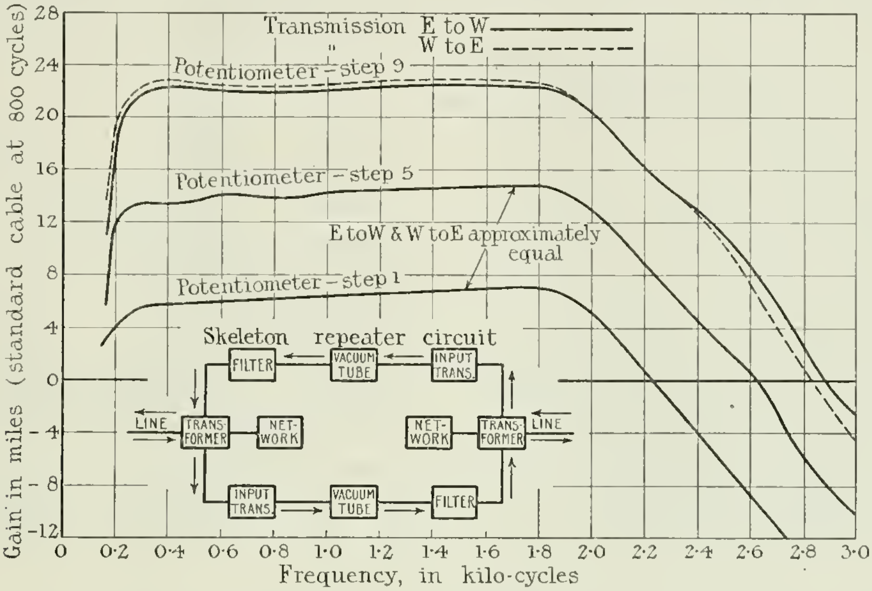


Fig. 5.—Gain/frequency curves of 22-type repeater.

First let us look at the general types and their places in the system. There are, so far, three general types. First, the repeater which operates in two directions by means of a single amplifying unit, the so-called 21 type repeater; this must be placed at or near the centre point of the line because the impedances of the lines on each side of the repeater act as balances to each other, and, if they are not equal, the unbalance will cause circulating currents round the repeater, with the result that sustained oscillations will be set up and the repeater will "sing." Up to the present, this type cannot be used in tandem, consequently its use is limited. It may be applied either to open wire or to cable circuits. Second, there is the repeater which operates in two directions by means of two unidirectional amplifying units, the so-called 22 type repeater. With this type there is much greater freedom in locating the repeater, because the balance is not between the two impedances offered by the lines on each side of the repeater, but between the impedance of one line and that of a network made to simulate the line impedance, and the precision with which the network does simulate its associated line at all speech frequencies governs the degree of amplification or gain which may be taken from the repeater. If the balance is not held, circulating currents will cause the repeater to sing. Repeaters of this type are applicable to open wire and to cable circuits. They may be, and are regularly, placed in tandem, and as many as 23 have been used in tandem in regular service on a single conversation. This fact illustrates that the speech currents are transmitted with sufficient accuracy, as, otherwise, cumulative distortion would quickly cause degradation of articulation to an intolerable extent. Third, there is the repeater which operates in one direction only, the speech currents in the other direction being provided for by an independent circuit, the so-called 4-wire circuit, in which the currents from, say, East to West are taken by one circuit of two wires, with its unidirectional repeaters in tandem, and the speech currents in the other direction (from West to East) are taken by another circuit of two wires, also furnished with its unidirectional repeaters. Obviously, if a special 4-wire line were set up from subscriber A to subscriber B in which the circuit started with A's transmitter and terminated with B's receiver, and the circuit in the other direction were similarly treated, there could not be any circulating currents at all. Commercially, however, this is not possible, and it is necessary to use the regular 2-wire local system, so that only the long line portion of the circuit can be of the 4 wire type. With this type of repeater the circulating currents have to travel a long distance, which gives rise to great attenuation, before they can get back to their starting point for re-amplification, that, is, singing, and so a much greater gain can be taken from 4-wire repeaters than from 21 or 22 types, before the singing condition is approached. While the 4-wire type can be employed on either open or cable circuits, the fact that it required four wires makes it economically more suited to cable circuits; and since the gains obtainable are high (they can be made so high as to render the line loss zero between the terminals of the 4-wire section, which cannot be achieved by any other type) it is economically possible to employ this type of circuit in cable for distances up to 1 000 miles—perhaps further—and so it is pre-eminently suited for groups of long-distance lines carrying heavy traffic.

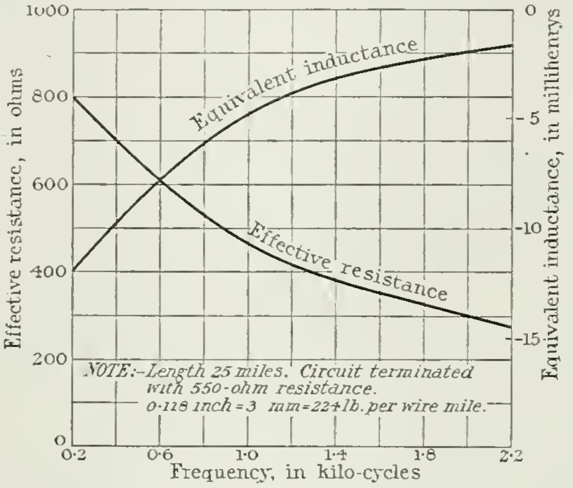


Fig. 6.—Impedance/frequency curve of 0·118 in. open wire non-loaded line.

Whichever repeaters are employed in any line they must, of course, be located at the right positions determined by engineering considerations alone and not by political ones. It might, for example, be correct for a line to run through Switzerland with no repeater on it at all in that country, or for a line to run through Limburg on which there would be a repeater in Holland, but no appreciable length of line in that State. In any such case the networks at the repeater in one country must conform to the lines situated in other countries.

The fact that telephone repeaters must be employed in tandem renders their requirements very severe. Fig. 5 illustrates the gains obtained from a repeater of 22 type, designed for a loaded cable circuit, taken at random and connected to an artificial line, the control of the gain being by a potentiometer with fixed steps. The top curve shows the gains from the two repeaters in the two directions, East and West, for speech frequencies when the two potentiometers were set on the same step, the ninth. The gain shown in the curve is approximately 22 miles, an energy amplification of 121 times. Of course it will be realized that this only shows what amplification the repeater can give; in practice, one would not expect such gains when connected to real lines. It will be seen how closely alike are the gains in each direction; that is, the speech currents are amplified in either direction with very nearly identical gains. When the potentiometers were set on the fifth step the gains were reduced, but the curves of the gain in each direction were practically indistinguishable, and the same held good when a still lower gain was taken by putting the potentiometer on the first step.

It will be noticed that these results were obtained, not by any careful and fractional adjustment, but merely by setting the two potentiometers on similar steps; and it will also be seen that the variation in gain produced by one step is approximately 2 standard miles. The small inset diagram indicates some of the pieces of apparatus involved, all of which have to play their part in the gain at speech frequencies, viz. input transformer, vacuum tube, output transformer, filter, and three-winding transformer in each repeating unit. The diagram does not show the potentiometers which are placed before the input transformers. It will be realized that the gain given out by the repeater must, of course, be adjusted to, and suitable for, the type of line with which it is to be used; also that a repeater is not a universal article which can be attached to any line regardless of its make up.

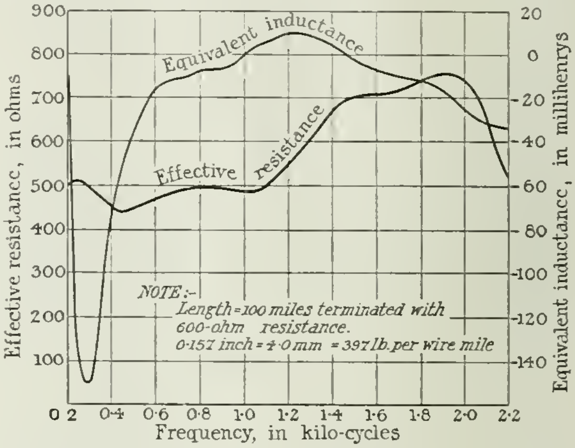


Fig. 7.—Impedance/frequency curve of 0·157 in. non-loaded open wire side circuit.

When, in actual service, repeaters are associated with lines, several reactions occur which very largely modify previous practice. As before stated, the line is balanced by an impedance network which simulates the line, but in order to keep these networks practicable it is necessary that the lines shall be as free as possible from irregularities, otherwise the networks would be very expensive and perhaps impossible. Fig. 6 shows impedance/frequency curves for an open wire line 41 km (25·5 miles) long of copper wires having a diameter of 3 mm (0·118 in.). This is an excellent example and so regular that there is no difficulty in providing a network which closely simulates the line; consequently, satisfactory repeater gains can be obtained. The indicated results were found at the first trial and without any clearing up. Fig. 7, however, shows similar curves for a line that was regarded as a first-class one until tests were made on it prior to using a repeater. It is seen that its impedance curves are very irregular, so that in its then state it was quite impossible to employ a repeater. Fig. 8 shows a cable circuit 34 miles (54·7 km) long, from which, for some unknown reason, the seventh loading coil, about 17 miles (27·4 km) distant from the place of this test, had been removed. The impedance/frequency curves very plainly show how, by this removal, the line is thrown out of balance with the network, and one can thus see that the removal of the coil would at once render useless the line of which it forms a part. The removal of a loading coil is a noticeable matter, but the want of uniformity introduced by several portions of a line having different constants, such as non-uniformity caused by the haphazard joining up of lines not constructed with a view to the rigid uniformity required for repeatered lines, acts in the same fashion.

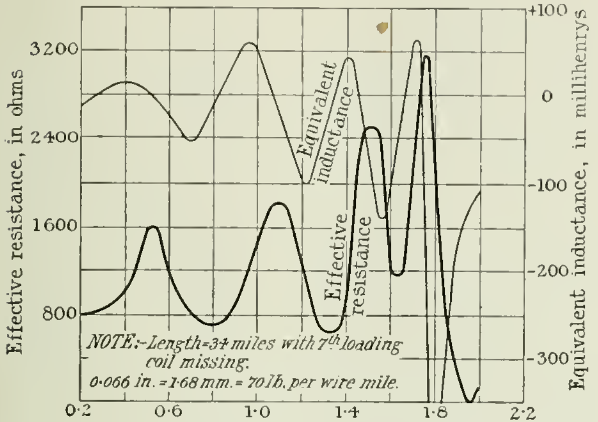


Fig. 8.—Impedance/frequency curve of 0·066 in. lightly-loaded cable circuit.

Fig. 9 shows impedance/frequency curves for a phantom loaded cable circuit 39 km (24 miles) long. It will be remembered that a phantom circuit is one which is obtained by superimposing the phantom on two circuits each composed of two physical wires, and it is not an easy matter to obtain a low unbalanced condition between the various capacities which make up such a circuit. In this figure are shown the curves for the line and for a theoretically uniform line, and it will be seen that the actual line does closely approximate to the theoretically perfect line.

Let us now see what is the overall result in transmission when employing a long line in which copper and repeaters both contribute to the effective transmission of speech—what, in fact, is the transmission afforded over the whole system. In Fig. 10 are shown frequency/attenuation curves for a non-loaded open copper wire line 3 400 miles (5 472 km) long. The curves reproduced are: (A) actual measurements on the line when using repeaters of a type designed for and suited to the line; (B) computations based on using imaginary repeaters giving uniform gains at all frequencies; (C) actual measurements when using repeaters suitable for other types of line but unsuited to this one. The line included 12 repeaters in tandem and the results are somewhat remarkable. They show (curve A) that the specially designed repeater in conjunction with the suitable line gives a fairly uniform overall loss, approximately 10 standard miles, between the frequencies of 400 and 1 800. On the other hand, curve B shows that the theoretical uniform-gain repeater if used would be very unsatisfactory, in that it would give a frequency/gain characteristic of a very undesirable kind and one which would greatly increase the frequency distortion. Lastly, curve C shows that a repeater suited to the character of one line, if used with another line to which it is unsuited, may give overall transmission of a highly unsatisfactory nature.

Since it is not yet practicable to transmit all frequencies equally, it is evident that some sort of a compromise must be made; and if a line is composed of several sections, on each of which a different compromise has been made, the final through result may be less satisfactory than need be, solely because of the fact that the compromises contain no unity of treatment.

When repeaters are in operation, they must maintain constant the gains to be given out or there will be serious effect on the speech. If we assume a 4-wire circuit between Rotterdam and Milan, 500 miles (810 km) long and having five repeaters in it, operating at gains of 23, 30, 30, 30 and 23 standard miles (S.M.) respectively, say an average of 27·2 each, we need only consider what will happen if the gains fall off, since the gains will originally have been set to be as high as safely allowable. Assume, then, that the line without repeaters has a net equivalent of 148 S.M. from which we deduct the repeater gains, 5 × 27·2 = 136, leaving the net loss = 12 S.M. Now suppose the gain at each repeater station for any reason at all falls off by 2 per cent; this will represent 0·54 S.M. each, or 2·7 S.M. for the five stations, and the net result will then be increased from 12 to 14·7 S.M., an increase of 23 per cent in the loss in the line. Should the gain on each repeater fall by 7·5 per cent the total additional loss will be 10·1 S.M., and the final net loss will be increased from 12 to 22·1 S.M.—an increase of 84·5 per cent. In this case the loss would be so great that probably the line would

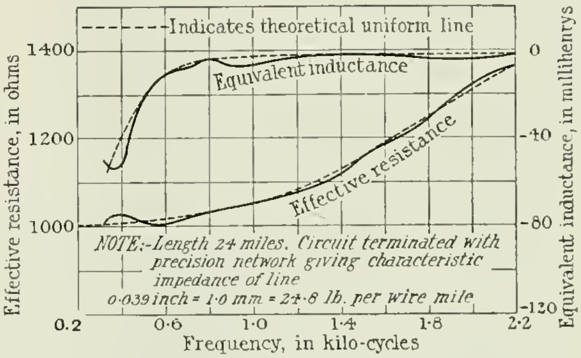


Fig. 9.—Impedance/frequency curve of 0·039 in. phantom cable circuit. Medium heavily-loaded cable.

become unworkable. I have chosen these examples to show the importance of uniformity of construction, uniformity of maintenance, and uniformity of operation ; it will be seen afterwards what is their particular application. The examples are rather understated than exaggerated ; it would have been quite reasonable to have taken a case with 20 repeater stations in tandem, and, furthermore, the gain given by a repeater would not in fact be one definite figure for all frequencies.

Fortunately, the design of repeaters has been carried far enough, so that, if correct design is employed and if certain regulations for operating routine and maintenance are followed, the gains can be held steadily ; but among those routines are tests which determine when the useful life of an amplifying element, a vacuum tube, has ceased, and the required constancy in gain can only be held if all repeater stations are operating to the same routine. If the line is an aerial one and subject to considerable changes in temperature, the resistance alters and another source of variation in overall transmission equivalent is introduced. If these changes are serious they can be compensated automatically ; if not so serious they can be dealt with by operative routine. The lesson is, however, the same in either case, and, for the best results, those persons operating the various repeater stations must be operating to the same routine, employing the same technique and under the one control. Again, when breakdowns occur important circuits cannot stand out of order, but must immediately be temporarily re-routed to restore the service. Such alteration may affect the balance between the network and line at the repeater station, and this may have to be dealt with by altering the gain of one repeater (in which case alterations will probably be required at all other repeater stations along the line), or by changing networks. If it were possible to foresee all possible combinations and emergencies, it would doubtless be possible, though not economical, to establish routines covering all cases requiring attention ; but obviously this is not possible, and the only commercial solution lies in unity of control of the line from beginning to end.

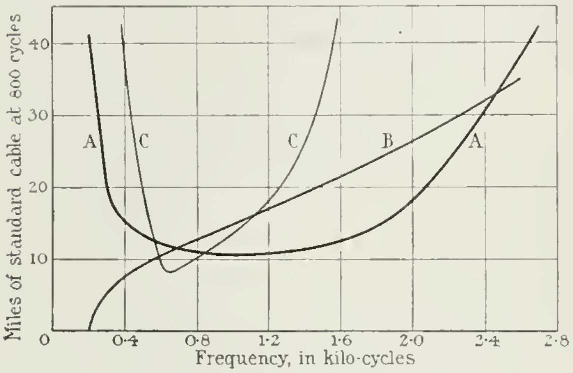


FIG. 10.—Attenuation/frequency characteristics of long open wire line.

It has been shown that the result of loading the circuit is reduced attenuation and somewhat impaired articulation in open wire circuits, and reduced attenuation and better articulation in cable circuits. Now that the use of repeaters has become possible, additional energy can be put into the line as required and the attenuation can be reduced by that means. It is therefore no longer necessary to sacrifice the quality which can be obtained on open wire circuits by loading them in order to reduce the attenuation—this reduction can be effected by repeaters. In cable circuits, however, it was shown that loading was necessary to reduce the frequency distortion. Consequently, long, heavy, open wire lines are not now loaded at all but are repeatered, resulting in improved articulation, and the increased speed of propagation avoids echo trouble, which only became insistent because of the more powerful effects derived from repeaters. With cable circuits, on the other hand, loading still obtains. It cannot be abandoned since it is necessary for the reduction of frequency distortion, but the tendency is towards lighter loading so as to raise the speed of the circuit, thus reducing the echo trouble which, because of the reduced speed and the great electrical length of loaded cable circuits, demands most careful consideration.

*Carrier circuits.*—In the search after increased capacity of telephone and telegraph circuits, there has recently been developed and put into commercial service the carrier system which has been added to the well-known methods of superimposing phantom telephone and compositing telegraph circuits. In this new method, carrier waves of different frequencies for each channel of communication are generated. If the channels are to be used for telephony such waves have a frequency above the audible limit. By means of band filters the desired range of frequency is permitted to pass into each channel, but only frequencies within that range ; thus on a 4-channel telephone carrier circuit the frequencies might range in four or eight separate bands with outside limits of 4 000 to 27 000 cycles per second. Each carrier wave is modulated independently by the voice currents to be transmitted by that channel, and all the modulated carrier waves, or all of one of the side bands only, without the carrier waves, are transmitted over the line. Upon reaching the far end, the waves are filtered out, each into its proper channel according to the carrier frequency assigned to each channel, and are then demodulated, leaving the voice current free to be farther transmitted over an ordinary circuit. Because of the increased frequency of the carrier waves, greater attenuation occurs with them than with the voice waves, and carrier current repeaters must be equipped more frequently than voice current repeaters ; also, for the same reason, carrier currents cannot be transmitted over ordinary loaded lines, which it will be remembered cut off at frequencies within the audible range. Hence, if loaded carrier circuits are required, they must be specially treated. Special treatment is also needed in the construction and maintenance of carrier lines and equipment, and because the equipment is expensive such lines must be of considerable length in order to be economical.

As an illustration of the advantages to be gained by using the latest development, the following may be quoted. On the New York–San Francisco line the circuits are of open wire from Harrisburgh to San Francisco, about 2 500 miles (4 050 km) direct distance apart. On four conductors on this route the loads carried are :—

2 physical telephone circuits,
1 phantom telephone circuit,
4 earthed telegraph circuits, and
a varying number of carrier telegraph circuits ranging from 6 to 20.

Two of the sections on this route in detail are :—

*Between Chicago and Omaha.*—450 miles (729 km) direct distance apart, four open wire conductors carry :

2 physical telephone circuits,
1 phantom telephone circuit,
4 earthed telegraph circuits which can be worked either 1 way or 2 way at will,
20 2-way carrier telegraph circuits.
—
27 total circuits on 4 wires.

This is shown in Fig. 11.

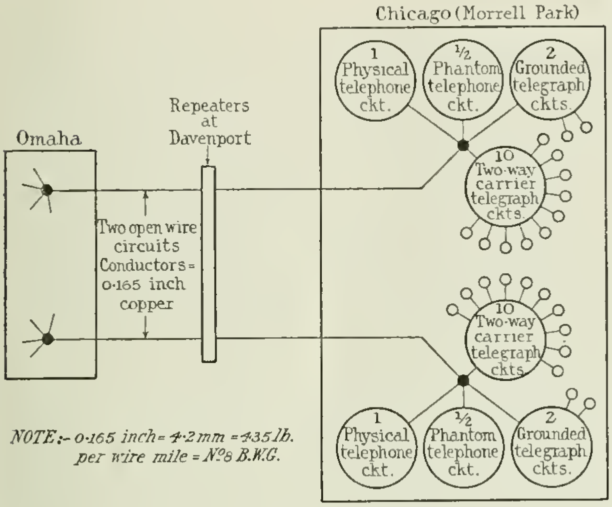

Chicago (Morrell Park)
1 Physical telephone ckt.
½ Phantom telephone ckt.
2 Grounded telegraph ckts.
10 Two-way carrier telegraph ckts.
Repeaters at Davenport
Omaha
Two open wire circuits Conductors = 0·165 inch copper
NOTE:- 0·165 inch = 4·2 mm = 435 lb. per wire mile = No 8 B.W.G.

FIG. 11.—Diagram showing the load carried on the Chicago–Omaha line.

*Between Chicago and Pittsburg.*—450 miles (729 km) apart, eight open wire conductors carry :

4 physical telephone circuits,
4 halves of phantom telephone circuits (equivalent to 2 circuits),
8 earthed telegraph circuits which can be worked either 1 way or 2 way at will,
37 2-way carrier telegraph circuits.
—
51 total circuits on 8 wires.

From another route we take the following :

*Between New York and Philadelphia.*—90 miles (145 km) apart, two conductors in cable carry, though not by carrier circuits :

1 physical telephone circuit,
30 special signalling circuits.
—
31 total circuits on 2 wires.

From Chicago to Omaha or from Chicago to Pittsburg the direct distances are about the same as from Paris to Berlin, from Paris to Marseilles, or from London to Milan. From New York to Philadelphia is about the same distance as between London and Birmingham.

At present there are in actual service in the United States the following miles of carrier route and channel :

| | Miles of Route | Miles of Channel |
|---|---|---|
| Carrier telephone .. | 4 776 | 16 576 |
| Carrier telegraph .. | 10 919 | 78 870 |
| Total .. .. | 15 695 | 95 446 |

*Cross-talk.*—Applications such as have been described demand a much higher degree of refinement, in order to avoid cross-talk, than those which have previously obtained in the construction and maintenance of long-distance lines. To obviate that evil, it is necessary that at every point throughout the entire length telephone lines should have the two sides of the circuit equal in admittance to earth and equal in series impedance, and these must be equal over the range of voice frequencies. This is a very severe requirement, but very good approximations to the result required are being made.

Fig. 12 shows the effective resistance unbalances for a non-loaded open wire 4·2 mm (435 lb. per mile) phantom circuit in good condition, and also with an unbalanced leak between one wire and earth, 147 miles away from the point of test. Unbalanced conditions may obviously arise by such defects as faulty joints, incorrect transpositions, faulty insulation, and apparatus faulty in design or maintenance. Further, cross-talk as an effect of unbalance is accentuated by repeaters, since too much energy delivered into a line may produce an intolerable amount of cross-talk.

*Interference.*—A matter which is assuming more and more importance is that which in the communication art is termed "interference," meaning by that term the reactions which occur between weak-current communication circuits and heavy-current lighting, power and traction circuits.

The effects of these reactions to the communication engineer may be serious and fall under the heads of :—Noise ; false signals ; breakdown of the line ; fire hazard ; acoustic shock ; electric shock.

Some consideration has already been given to the question of balancing the telephone circuits and, before looking at the same matter in regard to the power lines, perhaps it may be useful to give an idea of the relative trouble caused by different frequencies.

Fig. 13 shows the relative interfering effect of uniform currents at various single frequencies in a telephone receiver. The interfering effect is very unequal, and the importance of the wave shape in power circuits will be inferred from this curve.

On the power side, residual and balanced components of the power circuit voltages and currents may cause such trouble as to be beyond the ability of the communication engineer to cure. Every commercial three-phase system, for example, which has not been properly transposed is an unbalanced system, and any change in the separation of wires or height from the ground will affect the balance to earth, which generally is of more importance than balance of load between phases. This unbalance can be much reduced by transposing the power lines. Again, even if well balanced during normal operation, power lines are invariably thrown badly out of balance by abnormal occurrences such as the opening or short-circuiting of the line; and sometimes the circuit and switching arrangements are such as needlessly cause unbalanced effects, not perhaps noticed by the power engineer, but very troublesome, if not worse, to the communication engineer.

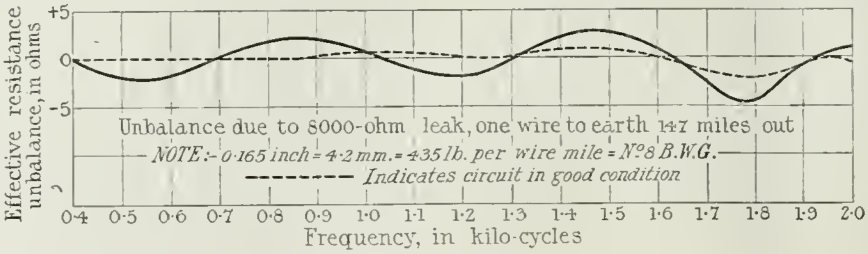


FIG. 12.—Effective resistance unbalance/frequency curve of 0·165 in. open wire non-loaded phantom circuit.

Now it must be recognized that these industries—involving the telegraph, telephone and railway signalling systems as representative of the light-energy group, and the lighting, power, railway and tramway systems as representing the heavy group—are both of them necessary to the well-being of the world, and they must learn to live together harmoniously and to avoid or mitigate the otherwise serious reactions between their respective circuits. It must also be recognized that in grappling with this difficult problem there cannot be, and ought not to be, any claim by either side for priority of protection or preferential treatment. It is wrong for the heavy-current interest to say: Let the light-current industry take care of itself. And it is equally wrong for the light-current industry to say: The heavy-current business must be conducted in such a manner that we, with our existing arrangements, shall be undisturbed. There is only one sensible solution. Let the engineers of the two industries first get together, unfettered by any partisan tie, to seek the best methods of getting rid of the trouble, and after those best methods have been found, on the basis of the least total cost, then, and only then, let the question of settling the apportionment of cost as between the interests be taken up. The ordinary difficulties of a complex situation are frequently rendered more difficult of solution by an endeavour at the outset to fix responsibility for the interference.

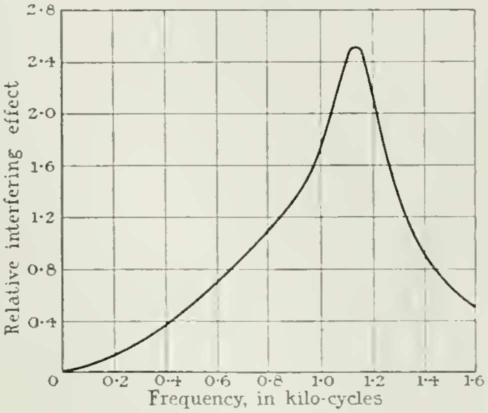


FIG. 13.—Relative interfering effect of single-frequency currents in a telephone receiver.

Much has already been done by joint study to reduce interference, and in some cases, such as those of electrolysis, it has been found economical to the "heavy" industry to avoid certain defects in construction which were first brought to light by the complaining "light" industry. But in all cases the lesson is always being pressed home, that success is certain to come when each party makes a real endeavour to learn the other's problems and to appreciate the efforts made by him to solve them.

Heretofore a long-distance telephone line was a relatively simple structure consisting merely of a pair of copper wires, either open or in cable; this could be maintained comparatively easily in good order by independent maintenance units situated along the length of the line. But with repeaters and loading, that simple structure has vanished, the plant is more complicated, and the various parts are interdependent on each other. It is no longer possible to consider maintenance of each part solely as a sectional matter—what is done at one place may cause serious reactions at another, and the line as a whole must be considered.

We can now, therefore, obtain certain advantages in the construction of through lines, but only if we are willing to give the attention necessary to secure them. It is false to imagine that we can obtain the benefits of the present knowledge without taking the necessary steps to secure them. The benefits are:

Great increase in the distance over which communication can be given.

Great increase in the number of channels of communication, telephone and telegraph, which can be provided by one pair of wires.

Great increase in the number of circuits which can be placed in cable, numbers such that it would be impossible to find space for them if all circuits were to be open wires.

Greatly reduced annual cost of circuits and improvement in quality of speech.

Increased security of service by reason of circuits being in cable.

Increased speed of service by reason of greater number of circuits.

The principal points to which attention must be given in order to secure the above advantages are :—

Definite decision as to the work each line is to do, that is, planning in advance.

Definite standards of performance to be required of the complete line.

Unity of treatment of all transmission matter affecting the line over its full length.

Unity of treatment of all transmission matters affected by the connecting of the line to other lines, whether trunks or subscribers' lines.

Unity of maintenance control over complete length of the line.

Unity of control over repeater gains over the complete length of the line.

Unity of operating control over the whole length of the line.

Education of all sections of the telephone staff in transmission, maintenance and operating practices.

Without this education among all detail members of the staff it is impossible to obtain the benefits now available. It is not sufficient for a few engineers in any administration to be familiar with these matters; they must be made part of the general knowledge of all, and this is particularly true of education in matters affecting transmission which must, by some means or other, in the varying degree required, be made to permeate all classes of the staff who have to do with the transmission plant.

The telephone service has certain special features, as follows :—

(1) The unskilled public is an actual participant in a call; the matter is not merely handed over to a skilled operator, although the skilled operator also participates.

(2) It is essentially a through service, i.e. the whole circuit embracing the calling and the called persons' instruments and the complete line connecting them are simultaneously in use for each call; therefore, all parts of the circuit must be harmonious, although these parts may belong to and be operated by different owners.

(3) The operators at the various stages along the line have to co-operate with each other, and differences in the operators' technique will decrease the efficiency.

(4) It is a world service, for it is impossible to set any limits to the service, which must extend as the degree of technical knowledge permits.

Frequently in industry one cannot obtain an absolute standard, and recourse must be made to relative comparisons. It is so in telephony, and as I assume that I may take it for granted, at any rate by those who have studied the matter, that the telephone systems of the United States are in advance of those operating in Europe, it is worth while to see wherein lie the differences (altogether apart from ownership), and particularly the differences in organization, and to obtain some idea of the telephone system in the United States, which now has nearly two-thirds of the telephones installed throughout the whole world. In that country there are at present over 10 000 companies owning and operating over 14 000 000 telephone stations. That total number divides into two broad classes: those having some kind of connection with the Bell System, and those which have not. Again, the first class divides into those known as Bell-owned, and others as Bell-connecting with an independent ownership.

We may tabulate the telephone statistics of the United States thus :—

| | July 31st, 1922 | | |
|---|---|---|---|
| | No. of Companies | No. of Stations | Per cent |
| Bell-owned companies .. | 26 | 9 223 770 | 65·0 |
| Bell-connecting companies (independent ownership) | 9 289 | 4 520 725 | 31·8 |
| Total Bell System .. | 9 315 | 13 744 495 | 96·8 |
| Non-Bell-connecting companies | 879 | 452 597 | 3·2 |
| Total .. .. .. .. | 10 194 | 14 197 092 | 100·0 |

In his Presidental Address in 1905 Sir John Gavey referred to the growth of the Bell System as "absolutely startling." He said there had been an increase of 1 450 000 stations in 7 years—an average of 207 000 per year. But since then the increase in the Bell-owned companies has been an average of 410 000 per annum, or twice the number which startled Gavey.

Taking the population of the United States at 109 millions it will be seen that there is now one telephone station to every 7·7 persons, while in the year 1900 there was only one telephone station to every 56 persons. Since the beginning of the twentieth century, while the population has increased by 45 per cent and the volume of general business (judged by the best data available) by 100 per cent, the number of telephone stations has increased by over 900 per cent.

Again, if we judge progress by capital expenditure, we find that the investment of the Bell-owned companies, which was $180 700 000 in 1900, had increased by 267 per cent by 1911, and by 755 per cent by 1921, and then stood at a total of $1 543 865 545, say £346 000 000.

As a method of trying to give an impression of the telephone service in the United States, it may be said that from his telephone in that country a subscriber can reach out over more than 4 000 miles and can call practically any of the 13 700 000 stations referred to, situated in 70 000 cities, towns and villages; and the statistics show that the telephone communications in that country outnumber the postal communications by 50 per cent. It is agreed by those best qualified to judge that American industry on its present scale could not function without the telephone service as they know it there.

From these figures it will be seen that, while there are many telephones which are not part of the Bell System, the great majority (97 per cent) are part of that organization of companies, and, further, it may be stated that with a few exceptions those companies which are not part of that system are, on the average, a collection of small concerns. In what follows, and generally in connection with the expression "telephony in the United States," the Bell System is referred to.

There are five outstanding features in the organization of the Bell System, and I think it may be said that these features are essential in any effective organization for telephony on an extended scale.

The five features are :—

(1) Local operating organizations, thus making for decentralization. These organizations, or companies, possess large measures of authority.

(2) A central administrative direction and control over the local organizations.

(3) A long-distance organization constructing and operating the long lines by which the local organizations effect intercommunication.

(4) Control of the manufacturing organization.

(5) A central organization for scientific research, development of apparatus and technique of construction, maintenance and operation.

In Europe, generally speaking, and considering the nations separately, we find :—

(1) An organization having a central authority with no separate local authorities.

(2) A series of administrative areas charged with the duty of maintaining the service under the central authority.

(3) No one department charged with the duty of through business.

(4) No control over manufacture.

When we consider Europe as a whole we find :—

(1) A number, about 40, of self-contained local operating organizations, each, in the majority of cases, conducting a local business and a through business within its area, also that part of the international through business which lies within its own borders.

(2) No organization controlling or co-ordinating the various local operating organizations, which yet have to function as a whole.

(3) No means of keeping the separate organizations in touch with each other, and no systematic means of adjusting differences in matters of daily practice.

(4) No organization of any kind which handles and cares for the through business as a whole.

(5) No common agreement as to manufacture.

(6) No common research, standard practice or technique of construction, maintenance and operation.

At the moment we are not concerned with the effect of this loose coupling upon the local business of each country, but little consideration is needed to appreciate its harmful effects upon the through business between countries, whether the length of line over which such business is conducted is great or small. There are in Europe large centres of population within such distances of, and in such commercial relationships to, each other that traffic would be forthcoming did adequate facilities but exist. There is no engineering difficulty, so far as distance is concerned, in constructing and operating lines at commercial rates to give satisfactory speech from any part to any other part of Europe, but at present the through business is meagre in quantity, slow and inefficient. Under the present conditions, practically the only way in which the nations can co-operate in these matters is that, when new lines are to be constructed between countries, there is co-operation and consultation between the representatives of the countries concerned, and occasionally there are international conferences. But these do not, and cannot, produce a unified system. All that they can do at the best is spasmodically and partially to compromise on a few outstanding differences in practice, which between whiles grow up unchecked, and to leave unsettled such large questions as cannot be agreed.

The settling of arrangements, and particularly the financial arrangements, for the construction of additional direct lines between contiguous countries constitutes an operation difficult enough; but when it is sought to construct lines between non-contiguous countries, in which cases they have to traverse countries not interested in the traffic desired by the terminal countries, the difficulties in the way of getting anything done are great indeed, and much praise is due to the energy and enterprise of those men who have succeeded in achieving the service now in operation.

Yet there is every indication that, given facilities, there is traffic waiting to be handled between the cities of Europe as between the cities of the United States. The opinion of some of those well qualified to judge is that the differences in language and customs do not, as they would at first sight appear to do, constitute a serious bar to international communication by telephony, and there are weighty reasons such as the present necessity of improving the relationship between nations, in addition to the normal commercial advantages, which render it safe to forecast sufficient through business to warrant the setting up of a competent organization with the plant necessary to handle the traffic.

There is, however, little likelihood of speedy and economical construction and operation of such lines as are necessary between, say, London and Stockholm, involving 3 or perhaps 5 intermediate non-interested countries, London and Kristiania involving perhaps 6 intermediate countries, or London and Petrograd involving 8 intermediate countries; and yet there is nothing fanciful in the idea of quick communication between such places. The direct distance between Brussels and Athens, or between Paris and Constantinople, is 1 300 miles—about the same distance as between New York and Omaha, or between Chicago and Salt Lake City, between which places calls can be made at any time. The direct distance over land between London and Bagdad is about the same as between New York and San Francisco, over which line conversations take place daily, while the direct distance over land between London and Delhi is about the direct distance from Key West in Florida to New York, thence to San Francisco and thence to Los Angeles, in California, over which distance calls can be made regularly. As a further encouragement, it may be said that the New York-Chicago cable, now in course of construction, will have a gross transmission equivalent so great that if a 435 lb. (4·2 mm) open wire circuit were constructed to that equivalent it might be 10 000 miles long, enough to connect Paris to the telephone system at Seattle in the North-West of the United States and leave enough to spare to take care of the cable across the Bering Strait. Of course, this illustration is uncommercial, but it serves to show that land distance is now no difficulty to telephony.

If we consider such business in the United States, we find that there are originated at New York over 4 000 000 long-distance calls per annum, and it will be remembered that in the United States many calls are made over lines of considerable length belonging to the local companies, and do not go over the long-distance lines. Similarly we find that Chicago and Philadelphia each originates something like 2 000 000 long-distance calls per annum, while such places as Boston, Cleveland and Pittsburg each originates about 500 000 long-distance calls per annum.

Fig. 14 is a map of Europe on which are shown a few of the long-distance circuits in the United States which are in regular daily commercial operation. It would have been easy to show a great many more, but this is not necessary in order to bring home the simple fact that there exists in that country a long-distance telephone service such as is not known in Europe. And yet there is no reason whatever why the service in Europe should not be extended in a somewhat similar fashion; from the fact of its denser population and less distant cities, Europe enjoys advantages over the United States, and these should make for much greater development of the through business than she now has.

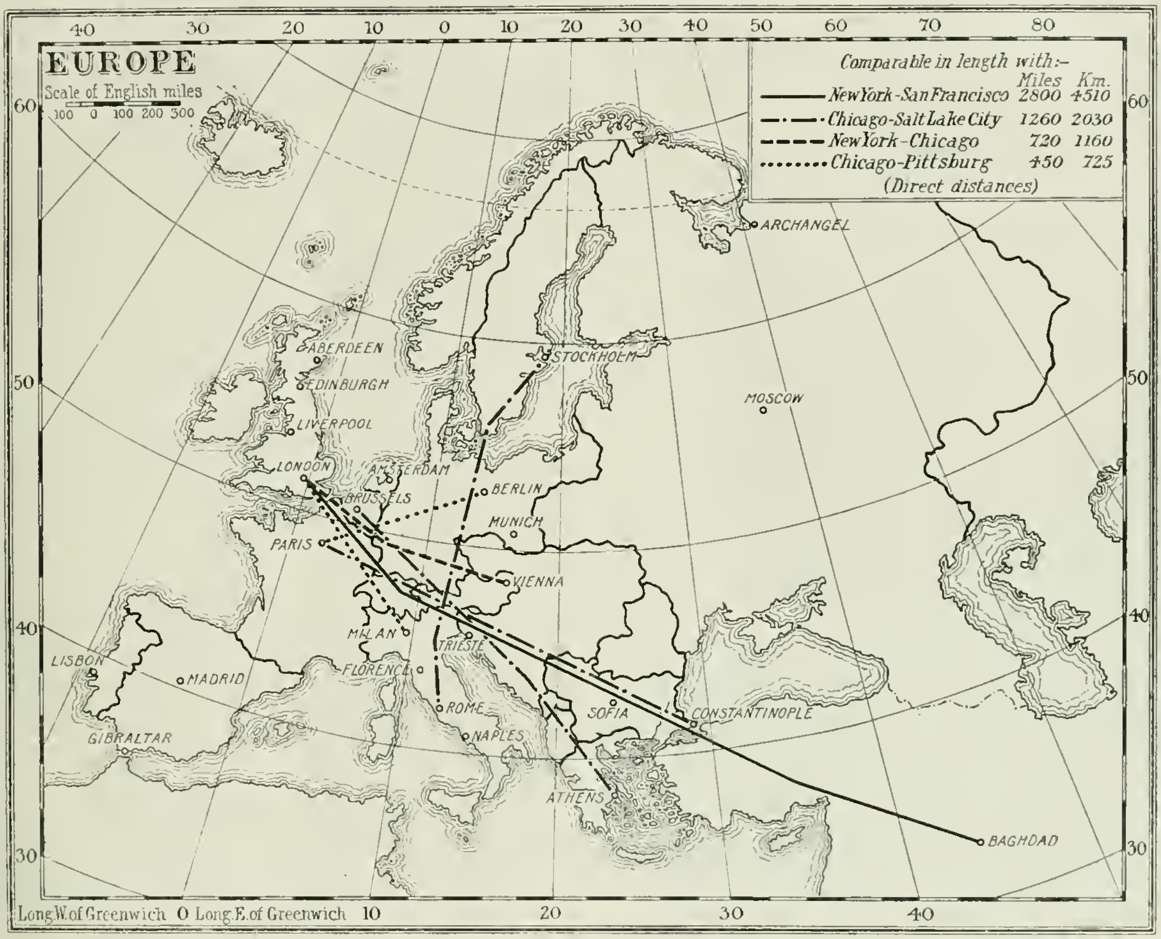


Fig. 14.

It is not putting the matter too strongly to say that through-telephony in Europe under the present conditions can never be worth the name of a service, and that the alternatives are either for ever to be condemned to an ineffective, inefficient state of affairs, or to find some plan, other than the present one, for dealing with the through business.

Analysing the conditions of through telephony in Europe as a whole, it is obvious that each nation, sovereign though it may be within its own territory, is really, from the telephone point of view, merely conducting a local business over an area which is not very great; it is also clear that no one local authority can operate its own through-business outside its own boundaries; although vitally interested, it must at its boundaries hand over the conduct of its business, in part, to someone else.

The through business must be handled as a complete unit if it is to be efficiently done; it cannot be done by independent units. The examples of recent improvements which I have referred to have been selected mainly because they illustrate the unity of treatment required by long lines. The correct course, therefore, appears obvious, viz. to depute a body to do for all European nations that which no one nation can do for itself. This is not a new departure; it is already practised by banks and railways in their clearing houses—no bank would now tolerate for a moment any attempt to effect for itself clearance of the various cheques presented to it daily, and consequently we find that the banks themselves have established their clearing house, which performs specialized functions for all banks, and thus expedites the work of all.

The corporate spheres assigned to any telephone authority may be determined by political, financial, legal or other considerations, and by reason of these spheres and considerations the authority is entitled to receive revenues and is obligated to pay the taxes and bills arising out of or payable in respect of those spheres. But these corporate spheres have, in reality, nothing whatever to do with the operating areas, which ought to be fixed solely with regard to obtaining the most efficient operating possible, and without any regard whatever to the corporate spheres. If the two differ, it is quite feasible for the operating authority to account as between any two or more corporate spheres without sacrificing any operating efficiency. Once the fact has been grasped that there is no reason whatever for the corporate spheres of influence and the operating areas to be identical, and that each requires quite separate consideration for its determination, there will be no real difficulty in arranging operating areas for efficiency and apart from corporate spheres.

With sectional, non-unified control over the various portions of the through business, it is not possible to design, construct and operate through-lines of communication in a manner capable of meeting the needs of the public. It has already been shown in what manner conditions in one part of the plant may react on conditions at another part, and how these parts may be distant from each other, so that in fact what is done in one country may render ineffective the efforts made in another country. It ought not to be necessary to labour this point, but perhaps an analogy may help. The through business is as much a unity as is military operation; we have seen the advantage gained by unity of command in warfare and no one would now advocate independent multi-commands such as were seen in 1914 and the early years of the war. If it was possible for the nations to agree on such unity of control for the purposes of war, it ought not to be beyond their powers to agree to a unity of control for the efficient working of the through-telephone business. It is not enough for the separate organizations to attempt to agree to a code of rules to which each shall subscribe—such an attempt would only be to court failure. The business is varying, flexible, and very much a living thing; it demands intelligent and prompt treatment of its many variations, it requires control from central points carrying with it the power to instruct persons at great distance in the routines and duties they are to perform, and such control can only be effected by a living authority always on duty.

Besides the engineering considerations which have been dealt with, there are weighty reasons connected with the matters of circuit lay-out, business policy, rates and operating, about which much might be said, showing the impossibility of giving an adequate through service without unity of control, but this is not the place to deal with them.

It is easier to analyse the conditions and to state the fundamental requirements for efficiency, than it is to propound a scheme for an effective organization. Yet some effort at a solution must be attempted, even though it is unlikely that the first attempt will be successful. Any solution must find some method of satisfying the financial needs of the business as well as the technical requirements. At present it is difficult enough for the various administrations to obtain from their Governments the money required for the construction of such plant as is demanded by their own traffic, let alone for the fostering of traffic by the construction of lines not yet called for by public demand, and for the construction of lines between non-contiguous countries, which lines, although demanded, are not required by the natives of the intermediate countries through which they pass. In fact, in spite of the reality that Governments can borrow money at a cheaper rate than can public companies, it remains true that Governments do find difficulty in raising the capital necessary for the legitimate demands of telephone development.

The alternative suggestions which present themselves are :—

(1) To operate all the through business both within and between the various countries in Europe by a single long-lines company working under licences from the various Governments, taking the calls from the local originating organizations, and being entirely responsible for them until turned over to the local receiving organization.

Governments would put the long-lines company into a proper legal position, and make it plain that the company had the goodwill and support of the country, and they would co-operate with the company in the handling of the traffic. It might also be found desirable to turn over to the company, either on purchase or rental, certain lines and equipment already in existence for handling through traffic.

The advantages of this course would be that unified control could be achieved at once. The service would be on an ordinary commercial basis, and, if the fees were correct, sufficient money could be raised to construct all lines and equipment called for.

(2) The second alternative is for the various Governments to form what would in effect be a private company or Commission, of which the Governments only would be the stock-holders, to do the work described in the first alternative, and from each subscribing Government the Commission would derive its authority in that country. The Commission being supplied by funds, on some agreed plan of participation by each Government, would be the sole judges of the plant to

be constructed and operated, within the scope of the moneys put at its disposal, and it would assume the ordinary responsibilities of a board of directors of a public company, carrying out all the necessary functions and periodically reporting results to those who supply the capital. It might be that all plant constructed in any country should belong to that country, and that the capital to be provided by that country should be its proper share depending upon the plant within its own borders.

In addition, the Commission could hire facilities, where economical, from the local administrations in cases where it would not be economical for the Commission to construct its own lines. Such lines could be hired on a permanent or temporary basis. In the first case, they would be paid for at a proper rate per year; in the second case, the local authority's lines might be made use of, and the compensation to be paid by the through-business Commission might be a proper portion of the fee paid by the public.

The above is the merest sketch of a scheme, but if it should find acceptance I am ready to put forward for consideration by the proper authorities a plan which I believe will be found to provide a basis on which the countries can be represented on equal terms and by which no unfair burden is placed on any country, and I believe that such a plan would result in better service and be self-supporting.

(3) The third alternative is frankly one of a temporizing nature, being intended only to cover a study of this difficult problem. It is that the various operating telephone authorities should form themselves into an association for the purpose of studying this and other matters. Such association might come about gradually if necessary, and regular meetings might be fixed for the purpose of studying a pre-arranged programme, which, apart from the larger question as to how the through business should be operated, might include the fixing of standards of measurement, performance and methods to be recommended to all, and to be enforceable on those who subscribe to the association.

If I may venture to make a definite suggestion, it is that the telephone authorities of Europe—including the United Kingdom—as telephone-operating authorities rather than as Government departments—should hold an early conference of all the telephone authorities, companies and municipalities as well as Government departments, to study in detail this problem and endeavour to find a solution. I am convinced that unity of control over the through traffic must obtain in the end, but whether the through traffic is handled by one organization or by many, there are matters which urgently require agreement for the improvement of telephony as an efficient agent for service in Europe.

Almost entirely, what has been said is limited to through communication by telephony. This is not because there is nothing to be said regarding local service, but rather because it seemed better to try to focus attention on what at the moment is the greatest telephone problem in Europe, namely: How shall the through business be organized? Fortunately, the solution of this problem has never yet been seriously undertaken and, the whole matter being quite open, there are no standing decisions to be reconsidered. The engineering considerations make it plain that the communication which is possible, both technically and commercially, cannot be established under the present disconnected organization. As with a progressing organism, the time has come when the organization must, if it is to remain efficient, change from unicellular to multicellular, and the various cells must take up special functions rather than all functions; in that way only can the whole organization make progress.

One way of increasing goodwill among nations—especially necessary to be encouraged by all means possible at the present time—is by greater and ever greater intercommunication by all methods. In the telephone we have the most perfect means of communication of which we know, immediate and perfect human speech with all its tones and inflections, and the ability by interchange of conversation to remove misunderstandings. If only we will use it, not alone will it benefit the industry of the nation, but we shall be making a definite step towards reducing the international jealousies and fears and increasing the goodwill without which there cannot be peace on earth.

To those many friends for whose kindness in supplying data and discussing the subject here presented I am greatly indebted, I owe and tender my grateful thanks.

# WESTERN CENTRE: CHAIRMAN'S ADDRESS

By F. Tremain, Member.

(*Address delivered at* Bristol, *9th October*, 1922.)

In the first place I desire to express the honour which I feel in being elected Chairman of this Local Centre of the Institution, the success of which I have very much at heart. It is nearly 40 years since I was elected a Member and I am the happy possessor of a complete set of the *Journal.*

As I was unfortunately prevented from attending the Commemoration Meetings at which I was invited to speak, perhaps I may be allowed to enumerate some of the difficulties experienced by students in the early days soon after the passing of the Elementary Education Act. Especially in the provinces, there were very few science classes or laboratories and practically none for technical subjects, as the City and Guilds of London Institute could not for many years find qualified teachers. I, with another telegraphist and the local linesman, a trio of enthusiastic students, persuaded a science master to let us attend his elementary class after we ourselves had passed that stage, in order to take the advanced grade. Our plan was to use Silvanus P. Thompson's "Electricity and Magnetism," and study the small-print notes at the foot of each page, giving the mathematical proofs, etc., whilst the rest of the class took the ordinary course. We wrote up our notes and the teacher corrected them week by week. The plan proved to be not at all bad, as it formulated our work, which students working alone often find difficult. We took ordinary grade telegraphy with the same teacher, although he declared that we knew more about it than he did, but again with the aid of the City and Guilds syllabus he formulated our work, and we all three passed in both subjects. We then worked for and took the ordinary grade in Electric Lighting and Power, using Thompson's "Dynamo-Electric Machinery" as it appeared, I think, first in the *Electrical Review.* Finally, some of us passed in all the qualifying science subjects, and subsequently obtained Honours certificates in both Telegraphy and Electric Lighting and Power.

I was then appointed a registered teacher by the City and Guilds Institute, but although we had a most alluring circular printed, promising inspection of main lines, etc., not a single telegraph clerk would join the class. My partner and I then started inventing, and our first suggestion was a central-battery telephone signalling system, for which we took out provisional protection. On being submitted to the Engineer-in-Chief of the day it was, however, rejected as useless, it being then (in 1885) regarded as essential that signalling batteries should be at the subscriber's end and not at the exchange end of the line. This was the year of the Inventions Exhibition and I attended a class for teachers, conducted by Prof. Ayrton, at the City and Guilds Central Technical College adjoining the Exhibition. The procedure was a lecture in the morning, followed by laboratory work and demonstrations of the electrical exhibits. The teacher students included an Irish priest, a Whitworth Scholar, a Japanese and two or three others. We drove and compared an electric and a compressed-air tramcar, and tested an Immisch motor for efficiency at various speeds with a Prony brake and such measuring instruments as we could arrange for voltage, current, speed, etc. The supply was not very steady and we had rather an exciting time getting simultaneous records of the various factors. At that time I was greatly interested in small electric motors for winding up the weights of Wheatstone telegraph apparatus and had already submitted a model to the Engineer-in-Chief of the Post Office. The Inventions Exhibition presented an opportunity for carrying out tests, and with Prof. Ayrton's permission we tested the efficiency of a little Cuttriss motor, the data obtained from which proved invaluable later. Subsequently the weights were abandoned, as were most of the train of wheels first in the Hughes printing instrument and afterwards in the Wheatstone apparatus, the motor driving the small remaining train of wheels direct. The Hughes as thus re-designed is still, I believe, the standard instrument in this country and on the Continent, wherever the instrument is largely used. Its final shape was, however, arrived at after many painstaking experiments.

These experiments were made two or three years after my first transfer to the Engineering Branch in 1887. There was at the time little or no development. Mr. Edward Graves was Engineer-in-Chief and Mr. W. H. Preece (afterwards Sir William Preece) was Electrician. These two gentlemen brought me on to their staff and I remained in London for 18 years. At the time of my appointment we numbered 10, including one draughtsman, but the Headquarters Staff now numbers, I believe, about 300. The annual expenditure on plant, extensions and maintenance was probably under £500 000, including the Stores and Factories Departments which are now separated from the Engineering Establishment. The Engineer-in-Chief of the British Post Office to-day is, I understand, responsible for an expenditure of £16 000 000 annually, and for the supervision and upkeep of plant approaching £100 000 000 in replacement value.

I wonder if our captains of industry realize the enormous potentialities of the well-equipped engineering students who come to them from the technical colleges. I have an uneasy feeling that they are better utilized on the whole in other countries. Any one of them, if developed to the utmost, might prove a mine of wealth in the illimitable field of electrical knowledge, technically developed. Yet we hear of freshmen to the factory, with brain and hand well-trained, being put on machine tools. We want more engineering research and some industrial psychology if this country is to hold its own in the application of electricity to the service of man. If our industrialists in the electrical field would spend only 1 per cent of their net revenue in research work and propaganda I believe that they would be rewarded a thousandfold.

When I first joined the Engineering Branch of the Post Office I was stationed as examiner at the Department's new instrument factory at Holloway, and was one of three officers who tested and worked all telegraph and telephone apparatus after it had passed a mechanical examination before issue for service. Every instrument made or repaired in the factory, or made by an outside manufacturer, passed through our hands and was subjected to a test for correct resistance, insulation and capability to work at a figure of merit which provided a factor of safety under working conditions. We also tested some of the material before use, including the conductivity, etc., of silk- and cotton-covered wire used for winding apparatus. On the bobbins of the various relays, etc., there was little margin for variation of gauge and insulation. The smallest wire used was of 2 mils diameter with a thickness of silk covering ½ mil, making a total overall diameter of 3 mils. It may be interesting to detail the method of testing wire in those days. The wire was first gauged over and under the silk covering, and any doubtful reels were taken out. The method of checking the overall diameter was to wind on a small taper brass bobbin, on which 1 inch was carefully marked off from the cheek at the larger end, as many turns as covered the inch, examining the turns with a watchmaker's glass. The average diameter was thus ascertained, but before thus winding the wire it was carefully measured out into 10-ft. lengths and checked as regards resistance. The lengths so measured were placed in a box on the face of which was fitted a substantial plug-switch to which the ends of each length could be connected inside. Through a window in the box could be observed the scale of a special thermometer on which a few divisions were divided into tenths. The coils remained in this box for several hours to settle down. The measurements of resistance were made by a standard Wheatstone bridge and a Thomson mirror galvanometer. The object of the box and plug-switch was to protect the wires from draughts and the heat of the hand in changes during testing. After being tested for resistance the wire was measured for diameter, as explained above, then wound on a small copper cage and plunged into strong sulphuric acid for 5 minutes, afterwards passed into water, soda-water and fresh water in turn, dried by evaporation and weighed in a chemical balance. From the weight, the diameter and the thickness of the covering were deduced. The conductivity was generally found to be a point or two over 104 per cent of that of pure copper, according to Matthiessen's standard. All these various processes were carried out to a degree of accuracy well within one-tenth of 1 per cent, and as they were not likely to operate all the same way the result was considered to be accurate within 0·05 per cent. This will appear to be a very elaborate process for such small quantities of wire. It must be remembered, however, that in telegraph relays space is limited and the electromagnets have to change their polarity with great rapidity when working at, say, 400 words per minute. The purest iron core and the finest copper obtainable were therefore necessary if the relays were to respond to the specified figure of merit. It must also be remembered that in those days electrolytic copper was not so readily obtained commercially. I will mention one other instrument-factory experience, from which perhaps a more useful lesson may be drawn. There passed through the factory annually many thousands of instruments singly and assembled in sets, such as repeater boards, and amongst the former some hundreds of Wheatstone transmitters. One part of the gear is a rocking lever locked in its position (right or left) by a jockey roller. In this way is secured the reversal of current which, controlled by the punched slip, sends the signals to the line. When no slip is used, equally-spaced reversed currents are sent, and at 600 words per minute (the highest speed which has been obtained) these reversals take place at the rate of 240 per second, thus giving the note C below the stave in the treble clef. It can be imagined, therefore, that this lever and its jockey wheel performed a very important function. The lever was specified to be 17 mils at the root and 12 mils at the tip, for the purpose of checking which a template was provided. I had on one occasion a dozen of these on the bench and I remarked to my colleague that, as I had been gauging these for six months or more and had never found one wrong, I thought we might well trust this to the mechanical examiners who had previously checked the dimensions by a similar gauge. To my amazement, before I had examined the 12 instruments the upper end of one of the levers proved to be too thick for the gauge. The examining mechanic when called in was incredulous and thought my gauge must have been mutilated, but it was proved to his satisfaction that his gauge allowed too great a tolerance. I need hardly say that the check was not abandoned.

An interesting experiment in testing the strength of material for submarine cables illustrates the great care necessary in drafting specifications. I was engaged in a famous Thames-side cable factory supervising the manufacture of a submarine cable. The material before being presented to me was tested on receipt from the manufacturers by the cable makers' representatives, and on one occasion I was called to see a large quantity of galvanized iron sheathing wire 0·280 inch in diameter which was said to be failing under a minimum breaking load of 3 500 lb. As there were six or eight barge loads in the delivery and the wire was said to be quite useless for any other purpose, the makers' representative was in some distress, and there was, of course, the danger of the sheathing process being held up for a considerable time if new wire had to be manufactured. I inquired how it gauged and was told that it varied a little but was within the limits of 3 per cent laid down in the specification which, however, stipulated the minimum breaking strain for wire of the exact diameter. I agreed to accept a slightly lower breaking strain if the gauge were low, but within the specified limits, stipulating, however, that test-pieces from coils which gauged higher than the mean should carry a proportionately higher load before breaking. We carefully re-examined selected coils with quite satisfactory results and the whole consignment was passed. I need hardly say that the specification was amended for future jobs to provide for this contingency. The material was, as a matter of fact, excellent and quite up to specification.

The manufacture and laying of the first London–Birmingham cable provided me with an opportunity of testing air-space cable both at the factory and on the road. In this length (117 miles) over 570 tons of copper and 1 600 tons of lead were used. The cable consisted of 76 wires which in the first sections were laid up very loosely in four-wire quad formation so as to obtain a minimum specific inductive capacity between the diagonal wires. After some miles of the cable had been drawn into the pipes and jointed, a test was made which proved that there was considerable cross-talk between diagonal pairs of wires. By an elaborate system of crosses at test-pillars this cross-talk was eliminated, but the remainder of the cable was made up in 38 pairs and these pairs were given a variable lay so that no two pairs should be similar unless three pairs having a different lay intervened. On the completion of the cable between London and Leamington I was deputed to carry out a very exhaustive test, and to equip the cable completely. One half was to be equipped with various telegraph systems including duplex, quadruplex and Wheatstone automatic on loops and superimposed; and the other half with telephone sets. Although the cable was not intended for telephone purposes it was thought well to try what could be done. All the circuits so provided were worked simultaneously without difficulty, and the efficiency of the cable was thus proved. The test for capacity, resistance and telephone overhearing involved more than 6 000 recorded observations, and the equipment of the telegraph and telephone circuits involved the use of a very large quantity of apparatus, including 25 telephone circuits for listening-in at different parts of the cable and 12 such circuits for conversations which might be overheard by cross-talk.

As was mentioned in Sir William Noble's recent paper * and my remarks in the discussion thereon, I initiated the first loading experiments in this country early in 1901. The plant and apparatus used had to be improvised, and consisted amongst other things of 40 drums of 4-pair 20-lb. telephone distribution cable in ½-mile lengths; about 200 telephone induction coils used for loading; various telegraph switches for changing the coils; telephone transformers used as bridge leaks across a speaking pair and for phantoming in the ordinary way; and, of course, a Wheatstone bridge, Thomson reflecting galvanometer and, later, a secohmmeter. The cable enabled a loaded and unloaded circuit to be made up, identical as regards the factors $K$, $R$ and $L$, and each 40 miles long with access to the circuits at every ½ mile. It was at these 160 points that the switches were required and each was a double-pole two-way switch. The most useful improvised loading coil was found to be the secondary winding of the 25/1 induction coil, the inductance of which was 70 mH. With two of these coils at each point, connected to the cable by switches so that either, neither, or two in parallel could be used, good results were obtained with two in parallel, giving, of course, 35 mH per point.

Bobbins of this size were next specially wound with two twisted pairs of 11-mil wire so as to get a greater range of inductance, viz. from 10 to 40 mH in each wire of a loop at each point; the coils having a total, in series, of 80 mH. With 37 of these coils inserted in 38½ miles of the distribution cable, excellent speech was obtained. This cable having served its purpose was dismantled and returned to the store. The coils were used for trials on the London–Leamington section of the Birmingham cable and, as the cable had not been jointed through to Birmingham, a short completed section between Leamington and Warwick was next utilized as an experimental length. Test-pillars gave access to the cable at 2½-mile points at which tents were erected for coils, switches, etc., the cable being looped to and fro at the ends to make up a circuit of about 120 miles of 150-lb. conductor cable which could be extended at the ends to 140 miles. Adjustable inductances were made, giving a range of 5 to 62 mH without an iron core, and up to 160 mH with a core. This core consisted of 50 of the smallest, soft charcoal iron wire procurable, slightly stranded and covered with silk, and cut up into suitable lengths for the coils. Four of these laminated cores were used to obtain the maximum figure. The coil windings consisted of four sets of 1, 3 and 9 layers brought out to terminals and so wound and connected as to result in a capacity of $0 \cdot 002\ \mu F$ between the A and B halves when all in use. The variations of inductance were obtained by joining these windings in series or opposition, e.g. $(A + B + C)$, or $(A + B - C)$ or $(B + C - A)$, etc., by means of switches, as well as by the insertion of 1 to 4 cores of iron. The coils were mounted in sets of 5 on a board with a protective cover and used in each tent. This proved to be an extremely useful arrangement and with it the best loading for all types of cable was ultimately determined experimentally. Cable circuits up to 200 miles in length were spoken through with aerial-line extensions of several hundred miles. The improvement due to loading, in terms of length, was found to be from 2½ to 3 to 1.

I will mention one more improvised arrangement involving the use of some 336 tumbler switches, fixed on a board in sets of 56 and arranged in 7 rows of 8. Each row of 8 was used to short-circuit or bring into use the inductances inserted in four pairs of wires. The 56 circuits were operated by means of a lath of wood and could be altered in a second or two, and as this was done at any one, or all, of six stations, the

---

* *Journal I.E.E.*, 1921, vol. 59, p. 389.

difference in the loaded and unloaded cable could be observed as often as desired. If alternate stations operated, the difference between 2½ and 5 mile loading could be observed. This also proved to be a perfectly satisfactory arrangement, as almost every conceivable combination could be arranged by varying the inductance values.

Based on the results obtained, standard loading coils were designed, but these have since been superseded by the hedgehog type of coil now being installed on the London–Bristol–Newport route and elsewhere. The cast-iron pots containing these coils weigh from ½ to 1¾ tons.

I shall only mention one other early difficulty necessitating improvization which may be interesting. Before the invention of the insulation-testing set known as the "Megger," I designed one with a horizontal pivoted galvanometer for use on the road. The trouble was to get the necessary voltage. On one occasion I cut about 10 cylindrical slices from each of 20 circular dry cells, and joining them in series found I could get a perfectly good test up to 5 000 or more megohms per mile. We therefore had 3 000 small dry cells made and fitted in boxes in sets of 50, brought out tappings to 4 terminals through safety resistances, and by using six of these boxes obtained the 400 volts necessary for a satisfactory test of dry-core cable during underground construction. Until the Megger came into general use these served the purpose quite well.

As an outcome of the experiments with the Birmingham cable, single-screened conductors were incorporated in the design of the cable, extending it through Warrington, Preston and Carlisle to Glasgow, with a branch from Warrington to Leeds and Newcastle-on-Tyne. Similar conductors were included in the West of England underground cable which extends from London through Bristol, Exeter and Penzance to Porthcurnow, for the Eastern Cable Company's service. The largest cable on this latter route, a sample of which is available here for inspection, is 3¾ inches in diameter and contains 32 pairs of wires and 72 screened conductors, the total weight of copper per mile being 9 tons, and of lead 20 tons. I believe that my estimate for this London–Porthcurnow cable, including pipework, drawing-in and jointing and testing equipment, was £328 000. The cable in the western sections of course became progressively smaller until at Land's End it was only about 1 inch in diameter. A comparison of this sample with one of the new London–Bristol cable now in course of completion illustrates the very great advance which has been made.

In the former cable 105 circuits (telephone and telegraph) are provided by means of 9 tons of copper per mile, apart from superimposing, while in the latter cable 308 pairs of wires are provided by means of 5½ tons of copper per mile, and the facilities for superimposing are much larger, as 154 circuits, apart from superimposing, would be provided with the 4-wire repeaters mentioned in Sir William Noble's paper. There are no screened conductors, such screening of telegraphs as is necessary to-day being provided by using one wire of a loop and earthing the other as a screen. Part of this cable will be extended to South Wales, and the cable and loading pots are, I observe, in position in the Bristol section.

The progress thus made in the 17 years since I left London for Newcastle-on-Tyne, on being appointed Superintending Engineer, is certainly very remarkable. Not only has loading increased the efficiency of telephone cables nearly three-fold, as I demonstrated, but by the use of thermionic valves in telephone repeaters a further four-fold improvement, at least, has been effected.

The improvement due to loading is perhaps comparable with that brought about in electric lighting by the substitution of metal for carbon filaments in lamps; but the further improvement brought about by the telephone repeater marks, I venture to say, a much greater relative advance in communication by telephone than that resulting from the use of the gas-filled lamp in electric lighting.

It appears to follow, therefore, that supply engineers have some leeway to make up, if they are to progress as much in their art as telephone engineers have in theirs. Until they obtain a 24-hour load for their generating stations the capital expended on their generating plant, substations, mains, networks and equipment, cannot possibly earn a full and adequate return so as to bring down the cost of energy to a competitive figure.

I was pleased recently to see in a Bristol newspaper a reference to a suggestion which I have been making to supply engineers for several years. I refer to the supply of hot water for domestic purposes, by the use of immersion heaters operated at night when so much generating and other plant is to a large extent idle. This question of thermal storage is, I think, well worthy of industrial research. There are probably in Bristol alone, for instance, 80 000 30-gallon hot-water tanks put out of use by the very extensive substitution of gas and electric cookers for the kitchen range. I suggest that if these were recovered and converted into lagged tanks, or otherwise insulated to prevent loss of heat and fitted with heating elements and such a valve as is fitted in gas and electric steam radiators for turning down the gas or cutting off the current when a temperature approaching boiling point is reached, an extremely valuable storage of energy would be provided. The electrical energy stored by 2½ million gallons of water raised 150 degrees F. in temperature is, I suggest, not to be despised. To compete with gas for heating water, electrical energy would probably have to be supplied at ⅓d. per unit. It might be worth ½d. per unit in view of the immunity which electricity provides from fire risks, but the fact that it can be controlled from a distance is an immense advantage, as is also the fact that it can be turned completely off, whereas gas controlled by means of a thermostat is only turned down.

My suggestion is that a simple vibrating relay should be devised to cut the heaters into circuit, one for each tank, at the will of the switchboard attendants, district by district. This could probably be done by superimposing on the supply network a signalling current, which would possibly be sent to certain areas in turn, so as to spread the supply for this purpose over the slack hours. In fact, if this plan is feasible, energy for this purpose could be supplied at any time of the day or night when there was a sufficient surplus. The thermostat would cut out individual tanks when they were sufficiently heated. For bringing this stored hot water up to boiling point, necessitating the addition of cold water and so conserving the supply, I would suggest the use of small superheaters on each hot-water tap in a house.

As regards the insulation of the tanks, it might be practicable, now that aluminium is getting cheaper and more plentiful, to provide an inner lining on the Thermos principle to existing tanks, exhausting sufficiently the space between the inner and outer walls.

A recommendation for this system, if it can be successfully introduced, would be the fact that if hot water is not used due to a day's absence from home, only the small leakage of heat would be made up and charged for, whilst for prolonged absence the supply should, of course, be cut off at the main switch.

Another utility suggestion which might be worthy of industrial research and exploitation is the following. We have heard of the superimposing of telephonic speech (with the necessary calling facilities by ringing bells, etc.) on transmission lines operated at 30 000 or even 110 000 volts. Of course on underground power cables of any length, or on networks, such speech could not be superimposed. The electrostatic capacity of such cables is too high; but signals of a moderate periodicity probably could be, and there are buzzers on the market which operate at the supply frequency and are intended to take the place of house bells and their batteries.

The supply frequency would, however, probably be too low for my purpose. My requirement is a note which will awake people from a dead sleep, say C in the middle of the treble clef which is, I believe, equivalent to 512 periods per second. Now, if a buzzer could be designed which would operate at this frequency only, I would suggest its use for waking people up, in preference to alarm clocks. If such a signal could be made to operate at several frequencies, a little above and a little below this, so much the better. These frequencies could then be sent over the network at, say, ½-hour intervals from 6 a.m. to 8 a.m. and the renter would be supplied with a small instrument on which he would plug in, or turn a pointer on a dial to the time at which he wished to be called. If in a city the size of Bristol 50 000 renters of this service could be obtained at, say, 10s. a year, an acceptable additional revenue would accrue to the supply company for a small expenditure of energy. I venture to offer these suggestions to the supply authorities for what they are worth.

I will conclude with something in the nature of a vision. When I was in the North of England I erected for telephone purposes trunk lines of **H** poles braced with iron rods and from 40 ft. to 60 ft. in height. One line ran from Shap, through Penrith, Carlisle and Gretna into Scotland, and on the East Coast a second line ran from Northallerton through Bishop Auckland and Newcastle over the Cheviots to Jedburgh; South and north in other districts they proceeded into Lancashire and Yorkshire respectively, and both into Scotland. Now Professor Robertson, in his Chairman's address * to this Centre in 1916, spoke of various ways of getting cheap power, and he suggested that the Clyde might be dammed. If the great tidal energy of this river could be conserved, converted, and sent down over these lines—which I suppose the Post Office will not require when they can provide trunk telephones underground—it should be possible to supply energy without undue expense to Manchester and Lancashire in general, as well as to the East Coast and Yorkshire. There are also the poles and the lines to every town and village in the country, and my dream is that nearly all overhead plant of this kind will in the future be used for power transmission. Much thicker conductors would have to be employed in some cases, but only a few of them, and the total weight and strain on the poles would probably be much less than at present. The Shap–Carlisle line probably carried 4 tons of copper to the mile. On the minor cross-country lines, energy for lighting and power could be conveyed to every town and village. Over these minor lines it would no doubt be possible to provide the telephone service by means of the high-frequency carrier currents to which I have already referred, or by means of telephone cables suspended on the poles when these are used for power transmission. This double utility should cheapen both services and might lead to the re-population of our rural districts, reviving their industries and greatly increasing the amenities of country life.

Main lines all over the country, having probably a route mileage approximating to 12 000 miles, will ultimately become available for other than their original purpose. May my dream come true, for the turn of the tide of population, at least in part, back from our great centres to the smaller towns and villages would undoubtedly help towards "the greatest happiness to the greatest number." The increased modern facilities for travel will also help to secure this, but not to nearly so great an extent as the widespread provision of cheap electrical energy for light and power and the revival of rural industries.

---

* *Journal I.E.E.*, 1917, vol. 55, p. 37.

# DUNDEE SUB-CENTRE: CHAIRMAN'S ADDRESS

By R. D. ARCHIBALD, Member.

(*Address delivered at* DUNDEE, 10*th October*, 1922.)

In surveying the progress which has been made in the design of electrical machinery during the last 20 years, it is interesting to note some remarks made by Mr. Swinburne in his Inaugural Address as President in December 1902 on the subject of "Some Limits in Heavy Electrical Engineering." * Touching on problems generally, he says :—

" It may be well, therefore, to try and look over some of the branches of our great and diverse industry, and see what obstacles are now opposing us, and what are likely to oppose us shortly, and whether the obstacles are insuperable or not. This sort of prophecy is much more difficult than the other, for there can be no credit twenty years hence in having said something that could not be done, even if it has not, while if it has been accomplished the position is still more difficult. Negative prophecy is thus unattractive. But the discussion of our limits not only may have a beneficial effect in making us more modest, but may be a much greater benefit if by focusing our attention on a limit of any development we find either that the obstacle is theoretically insurmountable, in which case we must go round it, or that it has to be scaled in a particular way."

Speaking of efficiency and output of dynamos, he says :—

" We are not likely to make much advance in dynamos now, as we are limited on one hand by the hysteresis loss in iron, which prevents our using higher inductions in armatures, and low permeability which limits our field and armature tooth inductions. It does not seem likely we will now find iron much better in either respect. Nor are we likely to find a better available conductor than pure copper. As insulator we have mica. It looks, therefore, as if we were within sight of our limits in dynamo and motor designs."

Mr. Swinburne went on to describe a type of dynamo in which the field was made to rotate faster than the poles, whereby the E.M.F., and therefore the output of a generator of given size and speed, could be increased. He suggested the application to traction motors of the inverse of this principle, whereby the same output could be obtained from a given size of motor at a lower speed. The principle is virtually contained in the Hunt and Creedy cascade induction motors now in common use, but as far as generators are concerned it never seems to have received much attention. Possibly it may be more developed in the future, but the need for such a complication has largely disappeared since the introduction of the turbo-alternator.

In the light of Mr. Swinburne's remarks, let us now rapidly review the developments which have taken place in the last 20 years and again glance at the limits or obstacles to further development with which we are faced.

In the development of anything new, whatever it may be, we always find that its design is founded on, and resembles some implement, machine, or even animal which performed the same function before. The dynamo was evolved from the physics department and retained the stamp of the physics laboratory for some time before the engineer took the matter in hand and turned out the dynamo as we know it to-day.

Twenty years ago this change had already practically taken place, for, although Gramme-ring and smooth-core armatures were still being made, they were chiefly for spares or for such purposes as organ-blowing where the hum caused by the toothed armature was objectionable. The bipolar type of field magnet was still lingering in sizes in which it ought to have disappeared, in spite of the arguments advanced in favour of four-pole designs. The reasons adduced for the extra long life of the bipolar machine in this country was that we employed higher speeds than they did on the Continent. But it was soon realized how wasteful in material the bipolar type was, compared with the four-pole machine, and nowadays we find the bipolar magnet only in small machines or in larger machines only where abnormal circumstances combine to make it more expedient, as in certain turbo-alternators and railway motors.

The interpole machine had not yet made its appearance 20 years ago, although the idea was by no means a new one. At that time the load at which a machine sparked was, as often as the temperature-rise, the limit to its output, and the introduction of interpoles had the effect of raising the sparking limit and making us pay much more attention to the question of keeping the machine cool.

Alternators of the Ferranti and Mordey types were still in use, though rapidly becoming obsolete, and the medium-speed alternator which was taking their place was little different from the present-day type. The large low-speed type was becoming even larger, but in a few years its days were numbered as far as steam engines were concerned and the turbo-alternator very quickly took its place. The behaviour of the rotary converter on 50-cycle circuits created doubts in the minds of some as to the wisdom of employing such high frequencies, but it can now be trusted to run automatically in many places. Developments have chiefly been in connection with the regulation of the voltage and automatic starting. Induction motors were largely of the open-slot type, following American practice. The open slots permitted coils to be wound on formers, and barrel windings to be placed in the slots in the same way as in d.c. armatures. The closed or semi-closed slot necessitated hand winding, which increased the cost of labour considerably, but since more iron was exposed to the air-gap the machine could be made smaller and material was saved. In America, labour was dear and material cheap so that the open-slot type flourished. The winding difficulties in the smaller sizes were soon got over, however, by the use of a slot-opening just sufficient to let the conductors of a coil in singly, and in the larger sizes, in which bar windings are used, by quick methods of soldering the connections of the bars which were pushed through the slots and then joined together. A great many inventions were brought out to get over the difficulty of starting the squirrel-cage type, but hardly any of these have survived, and with the simple induction motor we are not much further on in that respect.

---

* *Journal I.E.E.*, 1903, vol. 32, p. 9.

No radical change has taken place in the design of transformers. Some special types have dropped out and, excluding the progress in methods of cooling and insulating for high pressures, there is little to record. The gradual increase in the iron losses due to ageing was a trouble which has since been got over by the manufacturers.

Hopes of long-distance traction by single-phase commutator motors existed in those days just as to-day, but developments have not been in proportion to the hopes, though the single-phase motor has been much improved as far as sparking limits and outputs are concerned.

It would appear, therefore, that there has beenn o radical departure in the general design of electrical machinery during the last 20 years, and on comparing the appearance of an old machine with a present-day one the chief thing noticeable is the tendency to enclose the working parts in a dust-proof—or is it a fool-proof—case. This is a sure sign that no minor troubles, and also no radical changes in design, are expected.

Before reviewing the limitations which confront us at the present time, let us refresh our memories by examining in what way the output of an electrical machine is limited. We shall take as an example a medium-speed alternator of low voltage. The output is proportional to the terminal E.M.F. multiplied by the current delivered. The E.M.F. is of course fixed by the voltage of the supply to which the alternator is to be connected, but we shall leave out all limitations external to the machine and consider only those set by the material of the machine itself. We can increase the output by increasing either the E.M.F. or the current, and shall first consider the effect of increasing the E.M.F.

We can increase the E.M.F. by raising the speed of the machine. This increases the frequency of the alternations in the teeth and armature core, and therefore raises the temperature of the armature. It also increases the centrifugal stresses in the rotor. After a certain speed has been reached, either the temperature of the armature or the stresses in the rotor will set a limit to any further increase of speed. We could get over the difficulty by designing the machine with fewer poles so as to reduce the frequency of the alternations, and with a smaller diameter so as to reduce the centrifugal stresses, but on further increasing the speed we should eventually be faced with the same problem, and finally arrive at the two-pole turbo-alternator in which we cannot make the poles any less or the speed any higher. Our only way out of the difficulty now is to use a stronger material for the rotor, and iron in which the hysteresis and eddy-current losses in the teeth and armature core are less. But we can also increase the E.M.F. by strengthening the field. By doing so we increase the flux density in the armature. After a certain stage the magnetic circuit becomes saturated and an abnormal amount of energy has to be expended to get any further increase in the field and E.M.F. We can increase the axial length of the machine to get over these difficulties, but we cannot for mechanical reasons do this indefinitely, and we are soon up against the same trouble as before. Our only hope now is to find an iron with lower hysteresis and eddy-current losses and with a higher point of saturation.

This exhausts our methods of increasing the E.M.F., so let us now see how we can get more out of the machine by increasing the current. This will increase the copper losses in the winding and introduce further armature reaction. The former will raise the temperature of the armature and the latter will eventually bring down the E.M.F., so that the output is no further increased. We can neutralize the armature reaction by windings on the poles, and we can increase the section of the copper by widening the slot. But this would entail an armature of larger diameter, which is already limited by the speed. We can deepen the slots, but by deepening them we increase the eddy currents, the reactance voltage, and the tooth losses, so that the other limits will soon drive us back to the limit of conductivity of copper.

If we add a commutator we introduce, due to sparking, new limits to the current, and, owing to the flashing-over which occurs when a certain voltage between segments has been reached, to the E.M.F. The sparking limit can be raised by the use of interpoles, and the flashing-over point by the use of more segments, but there is a limit to the practical width of a segment, so that the use of a commutator sets an absolute limit on the voltage which a d.c. machine can give. I have said nothing about the voltage being limited by the strength of the insulation, for the other limits occur in a low-voltage machine long before the insulation question becomes of serious importance.

The position of affairs to-day is that we are face to face with the limitations due to iron losses and saturation, and the resistivity of copper. Some progress has been made in reducing hysteresis and eddy-current losses by alloying iron with silicon ; but we have discovered no better magnetic substance than iron, nor better conductor than copper. We may expect, therefore, that these limits will receive much more attention during the next 20 years than they have during the past. The Sayers dynamo recently described in the electrical Press is merely a further attempt to get round these obstacles by cutting out the armature-core losses and short-circuiting the idle parts of the armature coils, or practically doing away with end connections.

This is not the first attempt in this direction. Disc-type machines have been made on this principle for direct and alternating currents, but there are many objections to the disc construction, one of the most important being its weakness laterally, so that short-circuits are very apt to destroy the winding. It will be interesting to see to what extent centrifugal stresses will limit the speed and output of this machine.

If the dynamo of the future is going to avoid core losses, we shall have to face the problem of saturation and conductivity. We must bear in mind that these two factors contribute largely to the foundation of the heavy electrical industry. Were it not for the fact that iron is so much more permeable than other magnetic substances, and copper such a good conductor, electrical engineering would probably be by this time past its zenith. Certainly it looks as if further expansion of tramway systems is going to be very much curtailed. The trouble is that the weight efficiency of the internal combustion engine has improved a great deal and that of the electric motor very little.

Is the case quite as hopeless as Mr. Swinburne thought 20 years ago? The applied physics department is a new creation since those days and is busy on those problems at the present time. The exact conditions which render a body magnetic are not yet fully understood. We find that the alloys of some non-magnetic substances form magnetic ones and that alloys of some magnetic ones form non-magnetic ones; also that slight impurities affect the magnetic condition very greatly. It is too soon to say that anything is going to come of this, but further research along these lines will tell us before very long whether saturation is an obstacle which we must get round or can surmount.

When it comes to conductivity the alloys give us no help; for by alloying two metals we always increase the resistance. Experiments with metals at extremely low temperatures show that it is possible to make a conductor have practically zero resistance. It is hardly likely that this will find any practical application at present, though it does not seem beyond the bounds of possibility that it may some day be made use of in turbo-generators if the heat-insulation problem is not too difficult and the energy were transmitted to the external circuit by mutual induction to prevent heat being drawn from the mains.

The important point about these experiments is that they will probably lead us to the solution of the problem of what really is the cause of resistance. Then we shall know whether it is necessary to go to these low temperatures to get better conductivity. If so, and we can find nothing better than our present iron, the prophecy of Mr. Swinburne will probably be good for another 20 years, if not more.

I shall conclude by suggesting a problem towards which it might be advantageous for station engineers or manufacturers of generating plant to turn their attention.

Every effort is being made at present to obtain more effective means of cooling in turbo-alternators and this is a most praiseworthy object to have in view. But little heed is paid to the considerable difference which is made by introducing the cooling medium at a low temperature. For example, let the temperature of the cooling air of a fully-loaded turbo-alternator be $t_1$ at the inlet and $t_2$ at the outlet, and let the temperature of the windings of the alternator be $t_3$. Then $t_3$ is greater than $t_2$, and $t_2$ than $t_1$. The rise of temperature of the alternator windings is $t_3 - t_1$, and this is practically the same on a cold winter day when $t_1$ is low, as on a hot summer day when $t_1$ is high, The consequence is that the alternator may have a considerable overload capacity on a very cold day, and little or no overload capacity on a very hot summer day.

Let the output of the turbine be 100 and the losses in the alternator be 5, so that the output of the alternator is 95 and its efficiency 95 per cent. Let $t_1 = 60°$ F., and $t_3 = 150°$ F. at full load, so that the temperature-rise $t_3 - t_1 = 90$ degrees F.

Now suppose that there are 12 degrees of frost so that $t_1$ becomes 20° F. The rise of temperature being the same as before, $t_3$ becomes 110° F. and we are left with a margin of 40 degrees F. to work on. On the assumption that the temperature of the winding rises in proportion to the losses, we could increase the armature current in the ratio of $\sqrt{(130/90)}$ or 20 per cent, and bring $t_3$ back to 150° F. The capacity of the turbo-alternator is therefore 20 per cent greater than when the air temperature is 60° F.

Suppose now we artificially produce the cold by refrigerating the cooling air from 60° F. down to 20° F., and for simplicity let us suppose that $t_2$ is 60° F., so that the cooling air enters the alternator at 20° F. and comes out at 60° F., In passing through the alternator the air receives an amount of heat practically equal to the losses = 5. This, then, is the amount of heat we have to extract from the air to bring it down to 20° F. again. (If $t_2$ is less than the atmospheric temperature we should gain a little by using the same air over again.) To get cold air at 20° F. we might have to refrigerate down to −10° F. Now the coefficient of performance of a refrigerator working between the limits of 60° F. and −10° F. is theoretically 6·4. Refrigerators can get within 70 per cent. of the theoretical figures, but allowing for motor losses, etc., suppose that we take the figure as 4. This means that for every 5 units of heat extracted from the air only $\frac{5}{4}$ or $1\frac{1}{4}$ units of work need be done. This work must be added to the losses, which will now be $6\frac{1}{4}$ at full load. We can, however, increase the load by 20 per cent or from 95 to 114, and if we assume the copper loss at full load to be 1·5 the extra copper loss at 20 per cent overload will be $\left\{(1\cdot2)^2 \times 1\cdot5 - 1\cdot5\right\} = 0\cdot65$. The total losses are now $6\cdot25 + 0\cdot65$, that is, say, 7, and the efficiency is

$$\frac{114}{114+7} = 94\cdot2 \text{ per cent.}$$

Hence with a small loss in efficiency the capacity of the station is increased by 20 per cent if the steam turbines and the boilers are able to supply the power. The cost of the refrigerator and the loss of efficiency would have to be set off against the cost of extra generating plant, but circumstances might arise where it would be useful to consider this point, and a liaison between the station engineer and the refrigerating engineer might elicit a number of things which neither had thought of before.

I suggest that this is a matter which might be explored to see whether any advantage could be gained.

# NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By F. G. C. BALDWIN, Member.

## THE PROGRESS AND POTENTIALITIES OF THE TELEPHONE IN THE UNITED KINGDOM.

(ABSTRACT *of Address delivered at* NEWCASTLE, *23rd October*, 1922.)

### HISTORICAL.

In the short time at my disposal it is quite impossible to give an adequate conception of the most interesting story which lies behind the development of telephony in this country. It is full of romance and it is perhaps astonishing that, so far, it has escaped more than very casual attention in literature.

On Wednesday, 2nd August, 1922, there passed from this life an inventor who, unlike many other such workers, lived long enough to witness the world-wide application of the fruits of his labour in the interests of humanity. I refer to Alexander Graham Bell, the inventor of the telephone.

Graham Bell really invented the telephone at Boston, Mass., on 2nd June, 1875, being assisted by Thomas A. Watson, an assistant in the electrical workshop of Charles Williams, whither many would-be inventors resorted for assistance in giving practical form to their ideas, and in the years which since have elapsed to the day of his death, at the ripe age of 75, he followed the development of his invention into an enormous industry and one which now furnishes a means of communication employed in every civilized country in the world.

The telephone is now so commonplace that one loses all wonder at its performance and is apt to forget what a really wonderful device it is; in fact, nowadays if it fails to give such constant service as is rendered, for example, by the domestic water tap, it is frequently condemned in no gentle terms. Yet it is extremely doubtful whether the announcement of any invention either before or since has been received with such incredulity or has excited such intense interest as that of the telephone. Mr. J. E. Kingsbury, in an address delivered at one of the meetings commemorating the fiftieth anniversary of the Institution,* refers to his vivid recollection of the feeling of awe which came over him on the occasion of his first experience of telephonic speech in 1878. Incidentally, telephone engineers might not be displeased if the telephone engendered some of that same feeling of awe amongst telephone users to-day and engendered a little more reverence for the instrument than is sometimes accorded it.

Telegraphy was the first real practical application of electrical science to the needs of mankind, and it was to forward the interests of electrical and telegraphic science that our Institution was inaugurated in 1871 as the Society of Telegraph Engineers. In 1878 the telephone was introduced into this country in commercial form; other branches of the electrical profession began to develop at about the same time and, along with telephony, grew into lusty branches before many years had passed. Although, in view of the ruling of the Court in the case of the Attorney-General *versus* the Edison Telephone Company, on 20th December, 1880, that the telephone was a telegraph within the meaning of the Telegraph Acts of 1863 and 1869, the designation "Society of Telegraph Engineers" might have sufficed to embrace the telephone also, yet the development of the sister branches of electrical science was so vigorous that the old title became inadequate to indicate the objective and scope of the Society, and, consequently, in 1881 it was altered to "The Society of Telegraph Engineers and Electricians," only to be changed again when the present title "The Institution of Electrical Engineers" was adopted in 1883.

For some time the telegraph and the telephone remained in the background, and it was not often that the deliberations of the Institution were directed towards the subject of telephony. So scanty indeed at one time were the literary contributions on telephony to the Institution and also to the technical Press, that it might not unreasonably have been concluded that the subject did not present a sufficiently wide field for exploration by the potential author. It was not, however, for this reason that telephone subjects were not more frequently treated.

While the principal telephone patents were in force the United Telephone Company was compelled very jealously to guard its rights and, while actively engaged in its numerous legal disputes, adopted a highly conservative attitude. Publication of its policy and methods of working were absolutely banned; at one time its officers were not permitted to read papers before the Institution and they were forbidden even to attend its meetings. Consequently, commensurate with the importance of telephony, there was a dearth of literature on the subject during the period in question, and it was a long time before the atmosphere created by the stringent secrecy and exclusiveness of the United Telephone Co. was dissipated.

The Post Office also has always been essentially conservative so far as publicity is concerned, and has never encouraged advertisement either of its policy or of its engineering and scientific achievements, although it has always been ready to furnish information and tender advice to interested parties. In comparatively late years only has telephony begun to take its rightful place in the proceedings of Institutions which exist for the advancement of engineering science.

The condition of the telephone system and the efficiency of the telephone service in this country have together been a source of keen discussion and the subject of no little criticism ever since the telephone became established as a practical proposition. In

---

* *Journal I.E.E.*, 1922, vol. 60, p. 428.

1878, people were amazed and almost incredulous at the idea of carrying on, by electrical means, conversation between points far distant one from another, and yet, in spite of the fact that telephone development in the United Kingdom has never been considered to be comparable with that which has occurred elsewhere, and particularly in America, progress was so rapid that in the space of a few years the old adage "familiarity breeds contempt" was once more exemplified, loudly voiced complaints being made that the telephone service was woefully inefficient, that speech was interfered with by extraneous noises, that sometimes conversation was interrupted, and that delays were experienced in establishing connections. Since that time vast developments and great improvements have taken place and yet similar and no less vehement outbursts of complaint are still not uncommon.

The master telephone patents did not expire until 1890 and 1891, and the United Telephone Co. which owned them during the greater part of the time they were in force farmed them out to other companies to exploit the provinces, and itself undertook the telephoning of London. To this Company fell the lot of guarding the patent rights which it held for the whole of the country, and so numerous were the infringements that it was found necessary to devote no little energy to this end, a fact which to some extent perhaps detracted from the main purpose for which the Company existed, namely, the provision of telephone intercommunication.

During, and for a little time after, the period in which the several subsidiary companies which had been formed were consolidated as the National Telephone Co., there was much organized agitation advocating treatment of the telephone question in different ways. The Government was greatly perplexed by the situation and the Company was kept in a state of suspense and doubt as to the outcome.

All this was not good for the telephone service, and the competition recommended by the Select Committee of 1898 eventually established by venture into the telephone field of certain municipalities, after prolonged agitation by them to be licensed to institute local telephone service, did not mend matters. On 5th April, 1896, the Post Office acquired the telephone trunk-line system of the National Telephone Co. in order that the revenue which it was alleged the long-distance telephone service withdrew from the telegraphs might revert to the Government and in order that facilities for inter-town communication might be available to prospective competitors of the National Telephone Co. The Post Office also entered seriously into the telephone business at about this time and in 1902 inaugurated its London telephone system. Recognizing the futility and serious disadvantages in the public interest of competition between rival telephone administrations, and in spite of the recommendations of the Select Committee of 1898, they wisely arranged in opening their telephone service to co-operate rather than compete, in the strict business sense of the term, with the National Telephone Co. for the remainder of that Company's license, and the metropolitan area was therefore saved from the throes of competition and the somewhat undignified proceedings which occurred in some provincial towns.

During the ten years 1902–1912, a most important and eventful period in the history of the telephone in this country both commercially and technically, Mr. Frank Gill, our President, occupied the position of Engineer-in-Chief to the National Telephone Co.

The election in this country of Mr. Gill as President of this Institution has been paralleled in America, where a similar honour has this year been paid to telephony by the election to the Presidential chair of the American Institute of Electrical Engineers of Dr. Frank B. Jewett, formerly Chief Engineer and now Vice-President of the Western Electric Co., the manufacturing and engineering section of that vast administration the American Telephone and Telegraph Co.

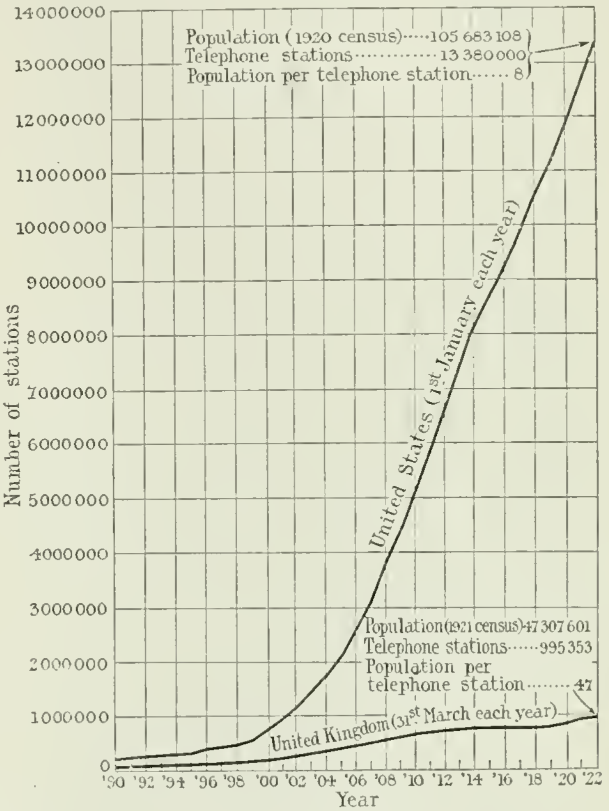


FIG. 1.—Comparison of telephone development in the United Kingdom and the U.S.A.

The Telephone Agreement dated 2nd February, 1905, entered into between the Postmaster-General and the National Telephone Co., which provided for purchase by the State of the Company's system, was the first tangible indication of the ultimate unification of the telephone system of the United Kingdom, but the agreement did not take practical effect until 1st January, 1912.

The total staff of the National Telephone Co. transferred to the Post Office at this time numbered approximately 18 000. Of this number about 7 000 were engaged almost exclusively upon engineering work and, when added to the existing forces of the

Post Office Engineering Department which numbered roughly 9 000, brought the total up to 16 000.

Within two years the staff had increased considerably and a good deal of work had been accomplished towards the unification of the system. Comprehensive schemes for the replacement of obsolete plant and the installation of new plant on a generous basis to meet anticipated development were in full swing when, unfortunately, the Great War intervened and put a stop for more than five years to all but imperatively necessary work.

During this period some 13 000, corresponding to more than 50 per cent, of the engineering staff of the Post Office, upon whom devolved the maintenance of the telephone service, were liberated for war purposes exclusively, and the remainder, in addition to carrying on the home telephone service under most trying conditions, also undertook services for the armed forces and associated with the Home Defences, services which have never been and never can be adequately realized by the uninitiated.

Since the armistice was declared, the telephone service has been carried on under difficulties no less than those which had to be contended with during the war. High, uncertain, and fluctuating prices, depletion of highly skilled staff, and shortage of the widely varying classes of materials and plant employed in telephony, have seriously delayed progress with the schemes which were in contemplation at the outbreak of war. Consequently, in many cases service has had to be and is still being carried on with plant that is obsolete and even past its physical life.

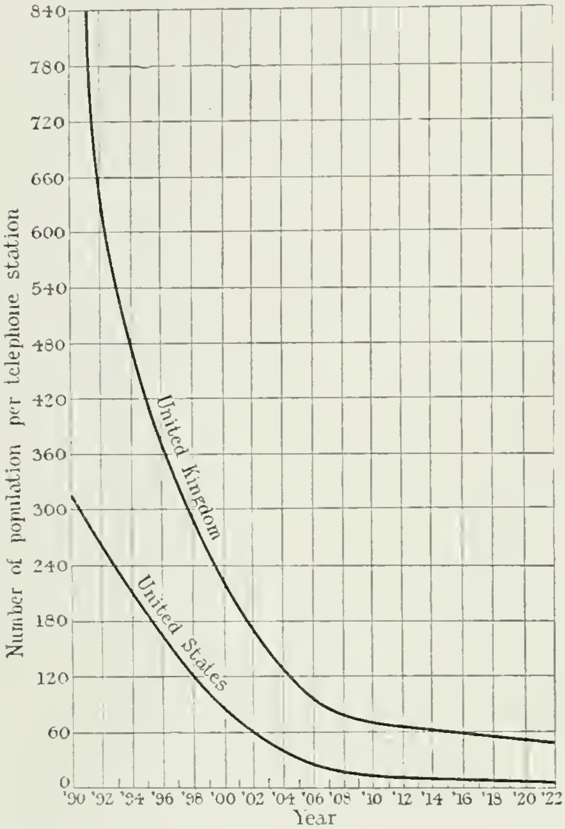


FIG. 2.—Comparison of the number of population per telephone station in the United Kingdom and the U.S.A.

COMMERCIAL DEVELOPMENT.

Development of the telephone in the United States since about 1900 has been phenomenal, until at the present moment there is one telephone station to approximately every 8 of the population, which totals approximately 105 millions. The development in the United Kingdom, with a population of 47 millions, has never attained to more than one telephone station per 49 of the population. The telephone development in the United States and in this country is compared graphically in Figs. 1 and 2.

It may be that the comparatively slow growth of the telephone in the United Kingdom is but a natural lag due to inherent British conservatism, and that in the near future the growth of the system on this side of the Atlantic may compare favourably with that which has taken place in America. Telephone development in this country will, however, depend primarily upon a return of commercial prosperity, and also upon a better appreciation on the part of the British public of the facilities afforded by a liberal provision of telephones in business houses and private residences.

I should like to take this opportunity of directing attention to the benefits to be derived by any community from extended use of the telephone. It will be obvious that the facilities afforded by telephone intercommunication service are increased with every subscriber added. I need not enlarge upon the advantages of telephone communication, but I venture to express the opinion that a large increase in the number of telephone subscribers would be highly beneficial to the commercial and industrial as well as the social life of the Kingdom. I have reason to believe that one of the causes why the telephone service does not develop satisfactorily is that many people refrain from becoming subscribers because the majority of those with whom they would desire communication are themselves non-subscribers.

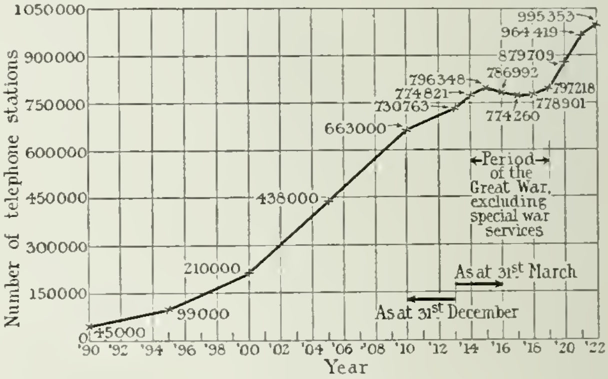


FIG. 3.—Telephone development in the United Kingdom.

So long as this conservative and somewhat illogical attitude continues it seems obvious that the telephone system cannot develop as it should, and the extended facilities which would follow from a more universal use of the telephone cannot therefore be secured.

The growth in telephone stations in the United Kingdom is illustrated in graphical form in Fig. 3. I have included this curve, which is similar to that shown in Fig. 1 except that it is drawn to a larger scale, in order to illustrate more particularly the effect of the war on telephone development in the United Kingdom. The unprecedented depression in the curve during the war period will be observed, as also the surprising fact that the loss sustained during the 4 years of war has almost but not quite been regained after a further 4 years, in spite of the difficulties which have been experienced.

### TELEPHONE SWITCHING.

The mere transmission telephonically of a communication between two fixed points is a matter which presents no great difficulty, and nowadays can be accomplished with little risk of interruption, but the introduction of the essential facilities for signalling and switching increases considerably the possibility of the occurrence of faults.

In the United Kingdom there are at the present moment upwards of a million telephone stations any one of which, with some comparatively few exceptions, may require connection with any other. When one considers for a moment the various operations and the numerous pieces of electro-mechanism possibly involved in the establishment of such a connection, and the combinations which are possible, the immensity of the system and its complexities may be more readily appreciated.

As is well known, attempts have been made in various ways to dissociate, as far as possible, signalling devices from the speaking circuit and, so far as is commensurate with efficient and economical practice, this has been effected.

The earliest switching appliances, from which the present-day manual switchboards have been evolved, were of a crude character. As early as 1879 there were two distinct types in use in this country; the one employed by the company formed to exploit the Bell patents depended upon flexible cords for establishing connection between one subscriber and another; the other, adopted by the Edison Telephone Co. which worked the Edison patents in competition with the previously mentioned and original Company, being an adaptation of the Umschalter switch much used at one time for telegraph switching. Thus the vexed question of the cordless *versus* the cord switchboard arose at an early date in the history of telephony, but the latter eventually proved its superiority, in spite of the trouble arising from the early type of flexible cord, and the cordless type of board was abandoned.

The rapid development of the telephone soon created, at the larger exchanges, serious difficulties in switching, which were eventually surmounted by the invention of the multiple.

It is not generally known that, although the multiple was invented and eventually perfected in America, it was devised independently in this country, much about the same time, by Mr. F. B. O. Hawes of the United Telephone Co., and two switchboards constructed under his direction were eventually brought into operation in London.

Unfortunately, Mr. Hawes did not benefit by his invention, being forestalled by the patenting of the American product in this country; consequently, multiple boards being essential here, they were for the most part supplied by the Western Electric Co. who acquired the patent rights. The first Western Electric multiple switchboard to be installed in this country was brought into service at Liverpool in 1884.

Early signalling was by means of batteries and ordinary trembler bells, which soon gave place, however, to magneto ringing, and the magneto system, apart from the call-wire system which was soon abandoned, held sway generally for a lengthy period, and, owing largely to the effect of the war, is still in considerable use although now regarded as obsolescent.

From the very inception of telephone switching in 1878, engineers have consistently striven to reduce manual labour in operating by the introduction of automatic appliances, with the object of minimizing the mental and physical effort of the operator, and of increasing the speed of operation and the number of calls which can be handled in a given period.

One might trace at some length the measures which have been introduced from time to time in the adoption of automatic devices as aids to manual operating, but it will perhaps suffice to mention only the step in this direction which was taken in the substitution of the common battery or relay system, as it was first termed, for the magneto system which it largely displaced. It is true that the prime purpose for which the common battery system was devised was to enable the primary batteries, previously necessary at the subscriber's station, to be dispensed with and current to be supplied to the transmitters from a centrally situated battery, but it is also true that by means of the relays and lamp signals, which form one of the salient features of the common battery system, the operating facilities were greatly improved, principally inasmuch as the operator was saved the labour of replacing by hand the shutters of electro-mechanical indicators.

The common battery system remains to-day very much what it was when first introduced in 1900, no drastic alterations either of the circuits or the mode of operation having been made. It realized expectations and a high standard of service was quickly reached, but it soon became apparent that there was little likelihood of any further material advance being made in telephone switching by this method, and consequently attention was turned to the possibilities of switching by machinery and the elimination, partially or entirely, of the manual element.

The introduction of full automatic switching whereby human intervention at the exchange is rendered unnecessary was not actually a natural development of the application of automatic appliances to the manual system. There were reasons why this could not be so. So-called automatic telephony was an invention which involved the employment of apparatus entirely distinct and different in principle and design from that employed in manual working, and was developed quite independently of the manual system which continued to be improved concurrently.

The removal of certain disabilities from which the automatic system suffered at first were essential before its adoption as a switching medium in this country was desirable, and it was not introduced here until its ability to fulfil the necessary functions satisfactorily had been demonstrated.

The period in which the automatic system was being developed in America was not a propitious one for its trial here. Because of its early expiring license the National Telephone Co. was disinclined to incur capital expenditure from which the financial return was doubtful, and it was therefore left to the British Post Office to conduct the first experiments in automatic switching in this country. These experiments were commenced in 1912 and were undertaken in order to ascertain:

(1) Whether automatic apparatus would fulfil satisfactorily the necessary switching functions.

(2) To what extent, if any, the British climate would affect prejudicially the operation of machine switches.

(3) Whether the British public would receive favourably the automatic system.

(4) The relative costs of machine and manual switching.

(5) The relative merits of the different systems on the market.

The first exchange to be opened was of the Strowger type, but since this system assumed practical form, a number of other systems have been developed, and the experiments conducted by the Post Office have included trials in actual service of five different systems in all, to which it is expected another will shortly be added.

A complete list of the automatic exchanges already opened and immediately in contemplation by the British Post Office is appended.

AUTOMATIC TELEPHONE EXCHANGES ESTABLISHED BY THE BRITISH POST OFFICE: 1912–1922.

| | Exchange | Type of equipment | Date opened | Capacity | |
|---|---|---|---|---|---|
| | | | | Of present equipment (1922) | Ultimate |
| 1 | Epsom .. .. | Automatic Telephone Manufacturing Co. | 18 May, 1912 | 600 | 1 500 |
| 2 | Official .. .. | ditto | 13 July, 1912 | 900 | 1 500 |
| 3 | Hereford .. .. | Lorimer | 1 Aug., 1914 | 500 | 900 |
| 4 | Darlington .. .. | Western Electric Co. rotary | 10 Oct., 1914 | 800 | 2 260 |
| 5 | Accrington .. .. | Automatic Telephone Manufacturing Co. | 13 Mar., 1915 | 700 | 1 500 |
| 6 | Portsmouth .. .. | ditto | 29 April, 1915 | 5 000 | 7 000 |
| 7 | Chepstow .. .. | ditto | 7 July, 1915 | 75 | 100 |
| 8 | Newport .. .. | ditto | 14 Aug., 1915 | 1 800 | 3 500 |
| 9 | Paisley .. .. .. | ditto | 15 July, 1916 | 1 600 | 2 150 |
| 10 | Dudley .. .. .. | Western Electric Co. rotary | 9 Sept., 1916 | 500 | 1 600 |
| 11 | Blackburn .. .. | Automatic Telephone Manufacturing Co. | 14 Oct., 1916 | 2 200 | 4 400 |
| 12 | Leeds .. .. .. | ditto | 18 May, 1918 | 9 600 | 15 000 |
| 13 | Grimsby .. .. | Siemens | 14 Sept., 1918 | 1 860 | 4 000 |
| 14 | Stockport .. .. | ditto | 23 Aug., 1919 | 1 300 | 2 260 |
| 15 | Ramsey (Hunts) .. | Siemens (Village) | 24 Oct., 1921 | 40 | 50 |
| 16 | Hurley .. .. .. | ditto | 20 Dec., 1921 | 25 | 50 |
| 17 | Fleetwood .. .. | Relay Automatic Telephone Co. | 15 July, 1922 | 480 | 700 |

AUTOMATIC TELEPHONE EXCHANGES ON ORDER BY THE BRITISH POST OFFICE: OCTOBER 1922.

| | Exchange | Type of equipment | Capacity | |
|---|---|---|---|---|
| | | | Initial | Ultimate |
| 1 | Dundee .. .. .. | North Electric | 3 500 | 5 000 |
| 2 | Southampton .. .. .. | Siemens | 3 500 | 5 500 |
| 3 | Swansea .. .. .. | Siemens | 3 200 | 6 800 |
| 4 | Marton (Yorks) .. .. | Automatic Telephone Manufacturing Co. | 80 | 230 |

The first three of the five questions previously enumerated have now been answered favourably to the automatic system, and it now remains to dispose of questions (4) and (5).

Time will not permit of discussion of the relative advantages of the automatic and manual systems of switching, nor of consideration of the several factors which are involved in determining the economics of the question. It is impossible to enunciate any rule for guidance in the choice of a system, either as between automatic and manual or as between the different automatic systems, and it is necessary that each case should receive consideration according to its distinctive merits.

Hitherto the policy adopted by the British Post Office has been confined to the application of automatic working to individual exchanges situated in various parts of the country, and in no case has a self-contained area including a number of exchanges been dealt with as a whole. Plans are, however, now in hand for the establishment of automatic working in a number of multi-exchange areas wherein the whole of the local traffic between exchanges situated therein will be dealt with exclusively by machine switching.

The problem of providing switching facilities by automatic means in an area containing several exchanges possesses many points of difference from the old problem in which manual switching only was concerned, and if, as seems highly probable, machine switching is introduced on an extensive scale the local telephone exchange systems of large commercial and industrial centres will differ in many essentials, other than the purely automatic one, from those to which we have become accustomed. Our previous conceptions and notions concerning the lay-out of large telephone systems will in that case need considerable adjustment.

With full automatic working in a local area, communication between subscribers connected to different exchanges may be effected as rapidly as between one set of switches and another situated in the same exchange, and the disadvantages which attach to junction working in a manually operated group of exchanges are therefore removed. Moreover, by reason of the rapidity of operation of automatic switches, a group of junction circuits may be worked at maximum efficiency.

These factors operate in the direction of increasing the number of exchanges and reducing the number of junctions which would apply with a manual system. As in a given area the number of exchanges may be increased, so the areas served by each exchange will be reduced in extent and the average length and, consequently, the cost of subscribers' lines are thereby reduced. Thus there are possibilities of effecting large savings in cost of line plant, a very heavy item in the capital investment of any telephone system, by the establishment of machine switching.

Automatic working possesses certain attractive features which commend it also for the supply of service in remote and sparsely populated districts. In country villages, where the number of subscribers is small and the traffic light, it is not reasonable to expect from the manual system the same standard of service as is applicable in an exchange where the number of subscribers is sufficient to justify unbroken attendance at the switchboard; and night service which, at some small country exchanges, is not at present available, is also a problem.

The employment of the automatic system at such places entirely removes those disabilities which are almost inseparable from a manually operated system, but, unfortunately, other difficulties of a technical and economic character are introduced which up to the present time have not been surmounted, despite the close attention already bestowed upon the question.

When the special problems pertaining to the village automatic exchange have been solved, as perhaps they may be in the near future, developments in the application of automatic working to such cases will, no doubt, proceed rapidly.

### Long-distance Communication.

There is something enthralling in accomplishing the interchange of speech over long distances and, ever since the telephone was first invented in 1876, endeavours have constantly been made to extend still further the distance over which telephonic speech might be satisfactorily conducted.

From a practical point of view the possibilities of long-distance communication within this country are definitely restricted by reason of its very limited boundaries, but in America, where the telephone flourishes more than in any other country in the world owing to the vast size of the continent, there are ample opportunities for development in long-distance service, and it is in America naturally where long-distance, as well as short-distance, service has been developed with great enterprise.

The longest distance across which telephone speech has, so far, been transmitted successfully is between Catalina Island in the Pacific Ocean and Cuba, a distance of something in excess of 5 500 miles. This distance included a length of 30 miles between Catalina Island and Los Angeles on the mainland bridged by a radio telephone connection; and between the Island of Cuba and the United States, the longest deep-sea telephone cable in use formed another link in the chain.

Up to the early nineties even the relatively low specific inductive capacity of the composite dielectric of the dry-core or paper-core cable was sufficient to render circuits carried in such cables greatly inferior in transmission value to the cheaper type of circuit comprised of bare overhead wires supported on poles, and consequently the latter form of conductor weighing up to as much as 800 lb. per mile was employed, to the exclusion of underground conductors except where the latter were absolutely unavoidable.

Although the limiting distance of speech over conductors of various types was fairly well known, and though the reason which limited that distance was partially but imperfectly understood, it was not until the theoretical works of Oliver Heaviside, published in this country so far back as 1887, were investigated and put into practical form and application by Dr. M. I. Pupin of New York in 1899 that the phenomena which accompanied the electrical transmission of speech came to be properly understood and a complete knowledge of the subject of telephonic transmission was built up.

The application of Pupin's work in the form of an inductance coil for the nullification of distortion and improvement in transmission, now known as line loading, and its results are already matters of past history and have become common practice. The application of line loading resulted almost immediately in extension of the use of underground conductors for longer distances, but the effect of loading in this country was, perhaps, more particularly in securing economy in underground line construction by a diminution in the gauge of wire required.

The benefits derived from the application of loading to subterranean conductors were insufficient to permit of the substitution of open by underground wires for long-distance circuits, even in this country. It is in fact only within the past year or two that communication by telephone over conductors exclusively underground from end to end of the country has been rendered possible by the introduction of the telephone repeater, a device which has been the dream of telephone engineers ever since the telephone was invented.

The application of the thermionic valve in the production of the modern telephone repeater is too well known to need further mention.

The long-distance telephone lines of this country are now steadily trending towards a comprehensive system of conductors of comparatively light gauge, laid exclusively underground, loaded at intervals of approximately 2 000 yards, linking up a series of repeater stations situated approximately 50 miles apart. Thus the one-time simple metallic loop between one centre and another is changing its form and becoming, as it were, more and more assimilated with the speaking apparatus. Although there are difficulties in the way, some known and some perhaps unknown, of which therefore it is yet too early to speak, there is little doubt that they will be surmounted in due course and that a long-distance telephone system immune from the interruptions and disturbances due to climatic and other influences, which are inseparable even from the best-constructed overhead systems, will be secured.

### Line Plant.

Since the resuscitation of Heaviside's theoretical work brought about by the investigations of Pupin, a fresh light has been thrown upon the functions of the line in the transmission of speech, and in very quick time an entirely new branch of telephonic science came into being under the term "telephonic transmission."

The result was what amounted to a revolution in underground line practice. The 20-lb. conductors universally used for subscribers' circuits soon gave place largely to wires of 10 lb. per mile, to be followed later by 6½ lb., and mechanical considerations chiefly limit the use in certain circumstances of conductors of still lighter gauge.

It became possible to design lines specifically according to the particular functions which they would be called upon to perform, and the altered aspect introduced many complexities in the design of economical cable systems. The problem is still further complicated by the provision which must be made for that unknown quantity, future development.

The considerations which are involved in the distribution of telephone lines are totally dissimilar from those which apply in the distribution of gas, water and electrical energy. With the latter, one main frequently serves a large number of consumers and, within certain limits, overloading may be resorted to without serious results; whereas for each telephone subscriber an independent pair of wires must be provided and maintained in a satisfactory state of insulation between each subscriber's station and the exchange. Consequently, a telephone line system has no flexibility apart from the special provision of spare conductors. Furthermore, water, gas and electricity supply are regarded as necessary, whereas in this country telephone service is not, and arrangements may therefore be made without risk for supply of the former into all premises. Telephone service is not by any means universal, and fluctuations are constantly occurring which it is difficult to cater for at short notice and reasonable cost. Consequently, flexibility is secured by completing distribution, wherever possible, by means of overhead wires radiating from distributing points to which a predetermined number of spare pairs of wires over and above the initial number of working circuits is provided.

In the construction of telephone lines the most notable advance made in telephone history has been undoubtedly the production of the dry-core cable.

Although the telephone dry-core cable originated in the United States, it is interesting to remember that as early as 1843 William Fothergill Cook invented, for telegraph purposes, a system of cable which was in effect "dry core." Metallic conductors insulated with a fibrous material were enclosed in an iron tube charged with air at a maintained pressure of about 3 lb. per square inch for the purpose of excluding moisture. The point of difference between the modern paper-core cable and Cook's system was that whereas in the former dry air is utilized as the staple insulating medium, the paper being introduced merely to maintain the wires in separation, in Cook's system the insulation was in reality dependent upon the permanent covering which enveloped the wires, but that covering was nevertheless rendered effective as an insulator by the presence of dry air.

A problem which has always presented particular difficulties is the effective termination of dry-core cable. Even to-day, after more than 30 years' experience, the means available for termination cannot be regarded as satisfactory and I commend the matter to those most intimately concerned for investigation, in the belief that a satisfactory solution would be amply repaid.

### Conclusion.

In this necessarily short dissertation I have attempted to give a résumé of the circumstances in which the telephone has been developed in this country from its establishment as a commercial project up to the present day, and to indicate very broadly its immediate possibilities.

Time has not permitted even casual mention of the many troubles which the telephone has experienced, but it will no doubt be apparent that the varied tribulations and vicissitudes through which it has passed have rendered its life a most eventful one.

It is now confidently anticipated that its troubles, if not ended, are at least moderated sufficiently to admit of a development which will be creditable to the country.

# LIVERPOOL SUB-CENTRE: CHAIRMAN'S ADDRESS

By B. Welbourn, Member.

(*Address delivered at* Liverpool, *6th November,* 1922.)

During the year it has been my privilege to pay a second visit to Canada and the United States, and to see for myself the immense progress which has taken place in all things electrical during the past 15 years.

## Telephony.

The first thing that impressed me was the extensive use of the telephone both for short and long-distance work. Owing to the high price of labour and the shortage of domestic servants, the telephone is a necessity in the majority of homes. The lady of the house has much of the housework to do and necessarily gives her orders to the tradesmen by telephone. In the hotels there is not entire privacy, as even in the bedroom there is usually a telephone.

There are now approximately 14 300 000 telephone stations in the United States. Of these, about 850 000 are on the Strowger system as made in Liverpool, and about 40 000 are of other types. The annual growth of all stations is 6 per cent, but it is significant that the annual growth of automatic stations is approximately 10 per cent. The telephone companies, of which the Bell System is by far the largest, make it easy for people to telephone or telegraph, and the use of both methods has become almost a habit. As illustrating the extent of the use of the telephone, I was told in Chicago that there is one telephone to every five people, while in Los Angeles, California, with 700 000 people, there are over 170 000 telephones, i.e. one to every four people, and telephones are there being connected up at the rate of 290 per working day with no sign of finality ahead. To many Liverpool engineers a very interesting feature of this will be that the whole system in Los Angeles is being converted to the Strowger automatic system as quickly as the plant can be delivered from Chicago. It was also interesting to learn that two exchanges are being equipped in New York with automatic telephones.

Long-distance telephony has made considerable progress, and it is now possible to telephone from Catalina Island, off the Pacific Coast, to Havana in the island of Cuba. This telephone transmission is of more than ordinary interest, as wireless telephony is used between Catalina Island and the Californian coast and is there joined in series with the land line to the Atlantic coast whence messages pass over the loaded submarine cable to Cuba—a distance of approximately 4 000 miles. I understand that, for this purpose, both the physical and phantom circuits are used over the land trunk lines.

Very severe gales with snow are experienced in the Eastern States, and the consequent disorganization of service in the winter is having the same effect as in England, namely, the placing of main transmission circuits underground with paper-insulated lead-sheathed cables to which Pupin loading coils and thermionic valve repeaters are attached, while experiments have shown that it is now possible to telephone experimentally over 15 000 miles of such loaded underground circuits, although the present commercial limit is about 1 000 miles.

One very noticeable feature in telephone work in America is the free way in which lead-sheathed cables are used overhead. In these cases the lead sheath is alloyed with 1 per cent of antimony to harden it and to improve the crystalline structure, and the cable is then suspended from a messenger wire by short supports at frequent intervals.

Among the interesting things shown to me were the first coil of wire through which the late Dr. Alexander Graham Bell sent his first telephone message, and the loud-speaking telephones used by President Harding when addressing a crowd of 100 000 people at the Unknown Soldier's funeral at Arlington Cemetery. Simultaneously, by means of special arrangements, he addressed audiences of similar size at San Francisco and New York. There appears to be no real technical difficulty in speaking simultaneously to audiences wherever there are telephone exchanges.

## Broadcasting.

Owing to the early lack of control in broadcasting stations, of which there are about 500, affairs seem to be in a chaotic state in the United States, and admiration was expressed for the leisurely but orderly way in which the matter is being tackled in this country.

It is estimated that there are about 2 000 000 wireless telephone reception sets in the United States, of which one half have been made by manufacturers and one half by amateurs. The manufacture appears to have outgrown the demand and the makers were said to be loaded up with unsaleable stock. Whether this was due to a seasonal slackness of demand, or to the interest in wireless telephony dying out, remains to be seen. It seems significant, however, that a good deal of second-hand wireless apparatus is being offered for sale.

In New York I had the pleasure of being present when Senator Marconi received the Franklin Medal of Honour and of hearing his address to the joint meeting of the American Institute of Electrical Engineers and the Institute of Radio Engineers. He dealt with the position of wireless telegraphy and telephony generally, and gave a good deal of information regarding his resumed experiments with 15-m wave-length telephony, with which he can now get commercial speech over a distance of 120 miles, together with very close direction. It would seem that the use of such a system, which is outside the ordinary commercial range of wavelengths, should have considerable possibilities for ship-to-ship and ship-to-shore work and also in public utility work, as considerable secrecy can be obtained. The advantages of ship-to-ship and ship-to-shore work under foggy conditions seem to be too obvious to need argument.

### Electricity Supply.

I hope to say something here which will encourage and stimulate electricity supply engineers to further efforts in promoting the use of electricity in this country.

To show the extent to which electricity is used for lighting in the United States and in Canada, I would mention that in the month succeeding my departure from Liverpool I saw only a single gas flare used for illuminating purposes; that was in connection with some suburban street lighting about 10 miles from Chicago. I did not, I think, see it again during the succeeding 25 days, except in the streets of Pittsburgh, Pa., where there is ample natural gas, and until I saw it from the Elevated Railway in New York through an open window of some old property.

The New York Edison Company alone has 600 000 kW of plant installed, and in Chicago the Commonwealth Edison Company has 626 450 kW, of which 230 000 kW is in the Fisk-street station. The maximum demand in this city was well over 500 000 kW in Decemer 1921. With a population of 2 700 000 people there are 536 982 consumers, of whom 425 200 are residence consumers, and the total number of kilowatt-hours developed by the company in 1921 was 1 928 271 940, i.e. 714 kWh per head of population. The number of new consumers added in 1921 was 62 287, and a car-load of meters alone is required per week to keep pace with the new service work. The total capital investment is $136 310 574, say, £30 000 000.

Let us compare these figures with those for Greater London with a population of $8\frac{1}{4}$ million people. Taking first of all the company and municipal undertakings, thus for the most part excluding all railway load, from the period 1919–1920 to 1920–1921 the total increase in the number of consumers was in round figures 25 000, bringing the total up to approximately 340 000. During the same period the increase in the plant installed was about 12 000 kW. There was an increase of nearly 40 000 000 in the kWh sold, bringing the total up to nearly 700 000 000. The total capital investment now stands at about £38 000 000, exclusive of the amount specially invested in power houses for transportation supplies.

To the above figures we can add approximately 560 000 000 kWh for the total units used for transportation, bringing the approximate total units for the last complete year to nearly 1 300 000 000, that is, about 155 per head of population. Comparing this with the 714 kWh per head of population at Chicago, it will be realized at once what an immense amount of leeway has to be made up in the capital city of our country alone before the use of electricity reaches the state of development attained by our American cousins.

At the risk of wearying you, I want to drive the point home by giving you data for the whole of the State of California and a few other places for 1921.

| | |
|---|---|
| Number of consumers in California .. | 843 011 |
| Connected load, in h.p. .. .. .. | 2 959 413 |
| Employees .. .. .. .. .. | 20 300 |
| Pay-roll .. .. .. .. .. | $31 227 496 |
| Taxes .. .. .. .. .. | $6 049 577 |
| Miles of wire .. .. .. .. | 127 382 |
| Oil consumed—barrels (no coal or wood) | 2 840 395 |
| Total investment .. .. .. .. | $448 669 330 |
| Total kWh generated .. .. .. | 4 000 479 010 |
| Total kWh sales .. .. .. .. | 2 662 653 511 |
| Power plant capacity .. .. .. | 1 463 009 |
| Total population of States .. .. | 3 426 536 |
| No of kWh per head of population .. | 777 |

In California, where the electricity supply is regulated by the Railroad Commission very much in the same way that it is governed in this country by the Electricity Commissioners, there is very little, if any, over-lapping of territory on the part of the electricity supply authorities. They seem to work together harmoniously and to have made many voluntary arrangements for the purpose of interchange of power. Practically 100 per cent of the houses in California are lighted by electricity exclusively, and, generally speaking, it may be said that the development of California depends very largely on electric power.

I should like to illustrate my meaning by giving a few particulars to show the way in which the electrical habit has been cultivated in this State. The Southern California Edison Company has 380 000 h.p. installed, chiefly in hydro-electric stations, and has so much faith in the future that it is proceeding with the development of an additional 1 220 000 h.p. The present output is distributed over their area of 56 873 square miles, with a population of 1 500 000 people by means of a network of over 10 000 miles of transmission and distribution lines. It supplies energy for 312 communities, furnishes power for 2 000 miles of interurban electric railways and for the irrigation of 1 000 000 acres of land. They directly supply 276 000 consumers, while other Southern Californian systems supply 240 000 consumers, thus making a total of 516 000.

Further north in the same State the Pacific Gas and Electric Company transmits and distributes over an area of 58 481 square miles with a population of 1 715 959 and 285 206 consumers, some of whom are distribution companies. To deal with this load, the company has a total installed capacity of 481 836 h.p., of which 421 750 h.p. is hydro-electric, and approximately 60 000 h.p. is steam-generated in oil-fired stations. Their supply is distributed over 9 971 miles of overhead lines.

Turning to our own Empire, we find rapid development in Canada. Apart from the great systems in Quebec centring around Montreal, etc., and those in British Columbia controlled by the British Columbia Electric Railway Company, etc., there is the large Government and municipal partnership scheme called the Hydro-Electric Commission of Ontario, which owns and makes use of generating plant at Niagara to the extent of 427 000 h.p., and other sources of power, is covering the whole province with a network of 110 000-volt and other lines and serves a population of 1 667 165. The Commission had 268 743 consumers on 31st October, 1921, with a maximum demand in June, 1922, of 360 268 h.p., and I saw for myself a great deal of the use which is made of the power from Niagara in the Commission's area from wayside farms to large undertakings such as that at Toronto. The Commission has succeeded in reducing very materially the cost of electricity to the consumer in Ontario, with the result that its use is extending rapidly. For instance, the Toronto undertaking had 12 000 consumers 10 years ago, whereas it now has 80 000. In Toronto the domestic consumption in kWh per consumer per month was 27 in 1914, whereas in 1921 it was 48, an increase of 78 per cent ; the wholesale rates per kWh per annum have been reduced from $18.50 in 1912 to $17.00 in 1921, a decrease of 8 per cent, while the net cost per kWh for the domestic consumer has been reduced from 4·4 cents in 1913 to 2·2 cents in 1921, a decrease of 50 per cent.

The question that I asked myself is : How is it that this great business is done ? In the first place one would expect that the electricity supply rates for power and domestic users must be considerably lower than in this country. With the exception of the Ontario scheme just referred to, I do not think that this is the case, but members will realize that it is difficult to make a direct comparison owing to the different money values obtaining in North America and in this country. I think that the real explanation lies in the fact that the use of electricity is a habit with most people in the United States and Canada. It has to be remembered that the United States and Canada are largely new countries where gas had not become well established when electric lighting first became available, and that the growth of most of the cities has been coincident with the electrical era. In many places both the gas and electrical interests are under the control of one company with men in high position who have rightly relegated gas to its proper function of heating purposes and reserved electricity for power and lighting. The advent of electric light into the home has been followed up by very active propaganda by salesmen of electrical accessories, while the companies have extensive showrooms in which prospective consumers can see apparatus in actual use before they commit themselves to a purchase. For instance, in Chicago the whole ground floor of the Commonwealth Edison Company's large building is used for showrooms. In these showrooms I saw, among other things, an excellent demonstration of a washing machine driven by an electrical motor, not as a special demonstration but as part of the day-by-day routine.

I do not wish to create the impression that the electric supply authorities in this country are unprogressive, but the figures that I have given show what an immensely greater business awaits them. Apart from railway electrification, which is only developing slowly, I would urge that much greater attention should be paid to securing the immense domestic load which may be as great as all the industrial business and less subject to trade fluctuations. This load is not to be secured by merely cutting the price of electricity, but it will require vigorous propaganda and salesmanship in the best sense of the word, the removal of all unnecessary restrictions, and arrangements to enable people to secure the apparatus without which they cannot use electricity. We are apt to forget that it is a feature of electrical appliances that their cost is frequently high compared with the value of the electricity which they consume in a year. To meet these points and to enable the electric supply undertakings to get some of the money which they now give to the gas companies and local merchants we must have :

(*a*) A reasonable but not necessarily a very "cut" rate for electricity.
(*b*) A system of hire or hire-purchase of the more expensive pieces of apparatus.
(*c*) In many cases, hire-purchase wiring of houses.
(*d*) A liberal practice in regard to
    (1) Laying of mains.
    (2) Showrooms.
    (3) Demonstration of apparatus.
    (4) Giving to the public what is generally known to-day as "service."

On the power side of the business in America most factories and the street, elevated, tube and high-speed interurban railways are run electrically, and there can be no doubt that with these already large loads a much bigger load awaits connection when the electrification of main-line railways really goes ahead. I hope that the electricity supply authorities in this country will see to it that they secure the supply of electricity to the railways as and when the electrification of main and suburban lines is proceeded with, so that there will be no waste of capital, and so that the load factor of the supply authorities' power stations will be improved. Immense loads are provided for the supply authorities by the local and express lift or elevator systems which are used in every important office building, and there would seem to be much room for improvement in this direction in our own country. At night, large blocks of power are used by the electrical sign advertisements, and no one who has seen the "White Way" in New York is ever likely to forget it. Despite the big power loads referred to, I was very much impressed everywhere with the steadiness of the pressure supplied to the consumers' terminals. The quality of the street lighting is also for the most part quite good and, in many important streets, the light on the road surface is equal to that in Portland-street, Manchester.

A question which is often raised, and which is sometimes difficult to decide, is whether it is better to place a generating station near the centre of gravity of the load or at some distance away and to give the supply through underground or overhead mains or, alternatively, to take a supply from an outside source, with a station at a considerable distance. In one area where hydro-electric power is used extensively, some interesting data and costs were placed at my disposal. The total cost per kWh at the power station busbars, including all capital charges, depreciation, etc., was 0·2 cent, whereas 0·35 cent per unit have to be added to this to cover all the transmission charges over a 250-mile line to the point of delivery, making a total of 0·55 cent, so that the cost of transmission is much more important than the cost of generation. In this connection I was surprised to find that the power available from some hydro-electric systems fluctuates more than one had imagined it to do. In the area in question in the past 25 years the rainfall has varied from 10·25 to 49·45 inches per annum, and most of this rainfall occurs in only three months of the year. It follows from this that steam stations have to be employed on some parts of the system and, in one case, 30 per cent of the units sold last year were derived from the steam plant. The steam stations in California are usually supplied with oil fuel, the price of which fluctuates considerably. Were it not for this latter factor and the feared exhaustion of oil supplies, it is not unlikely that more use would be made of steam stations, especially as, at the average prices of oil, the total cost of generation on the Pacific Coast is just about the same as the cost of hydro-electric power delivered over such long lines as the one referred to.

In view of the great discussion in this country since 1914 on linking-up, etc., I shall naturally be expected to say something about the security of supply.

(*a*) A great deal of interconnection or linking-up of power systems and stations has been carried out voluntarily. Probably the outstanding example of the value of liberal linking-up was illustrated in the spring of this year, when approximately 160 000 h.p. of generating plant broke down in one week in the various stations at Niagara, and yet the interruption of supply to consumers was negligible. An ounce of practice is worth pounds of theory.

(*b*) In big cities like New York, Chicago, San Francisco and others which have local steam stations and distribution by means of underground cables, the continuity of supply is, I believe, good. In other cities which are dependent for supply on overhead transmission lines and overhead distribution networks, the supply is not by any means so good, particularly in those districts where the overhead lines are much affected by lightning and snowstorms. The effects of snowstorms and gales were particularly felt last winter in Massachusetts, Ontario, etc., as reported in the Press at the time.

### TRANSMISSION AND CABLES.

So far as power cables are concerned, there is a good deal of experience in the United States with 24 000- and 13 200-volt, 3-core cables, and the records in the technical Press disclose that a good deal of it has not been happy. The troubles with underground cables appear to have been due both to defective manufacture and jointing and to overloading, partly under war conditions. In this connection, it has to be remembered that American engineers have mainly had to specialize in the development of overhead transmission lines, and the question of cables has been of minor importance. They are, however, now becoming much more important, and a great deal of attention is being concentrated on the development of 3-core, high-voltage cables, including those for a working pressure of 33 000 volts. The necessity for this arises out of the big loads to be transmitted and because of the attitude of the fire insurance companies towards overhead wires, especially as so many of the residences are built of wood, and because of the hindrance caused by wires to the fire brigades before they can get to work. From this it would seem that the use of underground cables will rapidly spread in the residential areas. The long transmission lines are a conspicuous feature of the electricity supply business in the United States and Canada, and in some places, owing to the absence of coal and oil, electricity must either be transmitted by them or not at all. They therefore have to be used, with their known susceptibility to lightning and storms. Troubles from these causes vary very much in different parts of the country. They are particularly bad in the Eastern and Middle West States, whereas on the Pacific Coast there is a noticeable absence of forked lightning and of snow, with the result that higher voltages are permissible there than elsewhere. It is right to add that there is abundant evidence that lightning troubles can be mitigated by the use of electrolytic and oxide-film arresters.

### TRANSMISSION PRESSURES.

The Great Western Power Company in California is successfully operating at 165 000 volts a.c., while the Southern California Edison Company will, next year, bring into use a 240-mile reconstructed line at 220 000 volts, and the Pacific Gas and Electric Company has just brought into use at 125 000 volts the Pit River–Vacaville 250-mile line which is designed for ultimate use at 220 000 volts. A great deal of the success or otherwise of transmission lines depends on the suspension-type insulators. It is notorious that these insulators were exceedingly unreliable until about five years ago and, in the interests of electricity supply generally, it is very satisfactory to know that makers in the United States and Canada, as well as one well-known firm in this country, have very seriously tackled the problem of manufacture and have developed products which can be used with confidence. In this connection I should like to say that it is my belief that insulators built to the new B.E.S.A. Specification No. 137 (1922) can be depended on for satisfactory service, but that when next the Specification is revised a high-frequency test should be added. In order to get the best practical result from such a test, it seems desirable that the wave trains should be damped so as to simulate as closely as possible those produced by lightning.

### GENERAL.

I wish to take this opportunity of acknowledging the hospitality extended to me by many engineers in the States and Canada, and to express my appreciation of the handsome way in which they placed information at my disposal.

# NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By W. B. WOODHOUSE, Member.

(*Address delivered at* LEEDS, *7th November*, 1922.)

I have to thank you for the honour you have done me in again electing me as your Chairman, and I hope that my year of office will see not only a continuance of the growth of this Centre and of the Institution as a whole, but also a marked improvement in the general prosperity of the country.

In choosing a subject for my address I felt that I might be forgiven if I confined my remarks to matters connected with the electricity supply industry in which I am engaged. My address in 1913 * dealt with one particular problem in connection with electricity supply, namely, the conservation of coal and the possibility of a general adoption of distillation processes and the production of oils, gas and ammonia from coal, the raw material of our industry.

All our elaborate supply systems are merely a means of distributing the heat energy of coal, and the proper treatment of coal is no less important to-day than fomerly. The commercial problem is so to treat coal as to obtain the greatest difference between the selling price of the coal products and the cost of the treatment.

The disadvantages of all the processes of distillation which have been tried are, broadly speaking, two in number. First, there is the cost of the process (wages, maintenance and capital charges), and secondly, the loss of heat, or the low heat efficiency of the process. Much work has been done since I discussed this matter in 1913 and progress has been made, though commercial success has not yet been achieved.

If the growing demand for fuel oils for internal combustion engines can be met from our national coal resources, the present steady growth of the use of oil for marine purposes may be regarded with equanimity; if not, the national wealth of coal cannot so readily be used to pay the nation's debts, and the country must suffer.

The electricity supply industry is particularly fitted to take a part in the solution of this problem; coal is dealt with in large quantities, and the process of electrical power production is a continous one—conditions which are essential to any economical process of distillation. I hope that an increasing number of those engaged in electricity supply will devote their attention to this subject and will make themselves familiar with gas-works and coke-oven practice as well as with the interesting research work into the structure and composition of our coals which is taking place.

Our present practice of producing power from coal by the agency of steam and the use of boilers and turbines shows a substantial improvement on the practice of 10 years ago; larger turbines and higher steam pressures are responsible for definite savings, and boiler-house practice also has improved.

The limits of the efficient use of steam in turbines have not yet been reached, but for the moment the greatest possibility of improvement seems to lie in the boiler house. Recent developments in the use of powdered fuel are of particular interest.

It has always seemed to me a little unfortunate that the efficiency of a steam-raising device consisting of a furnace, a means of releasing heat energy, and a boiler, a means of absorbing heat energy, should not be considered in two parts, separately. If this were done there is little doubt that more attention would be directed to the furnace than has been the case in the past, and as a consequence its efficiency would be improved.

Intimately bound up with that of the economical production of power is the problem of the working of interconnected stations, a problem which, I think, will be solved in large part by a moderate amount of study. For many years we are likely to continue the use of some smaller stations during factory hours, on account of the plant already installed and of their geographical position.

To ensure the economical use of such a station as part of an interconnected system, the establishment of a controlling engineer with autocratic powers is regarded by some as essential. It should not be overlooked, however, that private steam plants exist in many cases because of the needs of their owners for steam for other purposes, and that we must provide for the interconnection of these plants as well as for the public stations. Consequently, a single control in all cases seems likely to be difficult of attainment. I am disposed to think that the control necessary for economy and reliability may be equally well obtained by the influence of tariffs based on a closer study of the costs of working, and that it will be unwise to assume that a dictatorship is the only solution.

The cost of operating any steam plant under normal conditions may be analysed very simply, and the most economical method of interworking readily arrived at. A study of the problem should enable the provision for emergency conditions also to become clearer and more obvious, and it should not be difficult by consideration and classification to provide for security as well as economy, even though the generating stations remain under separate control.

Interconnected working need not, therefore, wait upon the creation of some controlling organization, more particularly as the possibility of the use of high-pressure direct current (the adoption of which would remove many present difficulties) seems within sight.

The power-supply engineer is frequently confronted with cases where power users, because of their requirements for steam for other purposes, are disposed to install exhaust or pass-out steam turbines. These cases will repay the most careful study.

---

* *Journal I.E.E.*, 1914, vol. 52, p. 30.

The exhaust-steam turbine is sinking into a position of relative unimportance, although at one time it was a powerful buttress of the reciprocating winding engine for colliery purposes. A study of the limitations of this combination shows that it must eventually disappear, except in very special cases, in any district where a public supply system is operating from large generating stations.

Another problem is introduced by the pass-out turbine, the limitations of which are naturally rather less known than the virtues claimed for it by the makers. There are definite economic limitations to the use of this type of machine, which will repay study and which indicate that the public supply undertaking need not despair of supplying all the power requirements of works where a large amount of steam is required at low pressure for process work.

As to the transmission and distribution of energy, definite progress has been made as the result of research and experience; from the greater attention paid to this subject a much clearer knowledge is being obtained of the technical and commercial conditions to be observed. The construction and use of cables for pressures above 30 000 volts, the rating of cables, and the continued testing of their state are all problems of great interest which deserve the closest attention of the electrical industry.

As to methods of distribution, the necessity for reducing the cost is urgent. Much good would be done, I think, by a free discussion of present methods, with the object of eliminating unnecessary work and cheapening the remainder.

Many undertakings have not for many years altered their practice in the method of laying mains and making joints, and there are other details of practice which would repay consideration.

Overhead line construction is also in a state of change. New regulations governing their construction in this country will be forthcoming at an early date and the satisfaction of these regulations at minimum cost is a matter of great importance, particularly in districts where the demand for electricity is not dense. Such problems as the design of supporting poles or towers and their foundations, the properties and behaviour of conductors, copper and other metals, and of insulators of porcelain and other materials, will well repay attention. The design of service lines for distribution at the pressure of use, and the many problems arising from supply in rural districts, should all receive attention.

In connection with all these problems the records of other people's work to be found in the technical Press and in such publications as *Science Abstracts* are of great value for reference, but something more is wanted. It would, I think, be of assistance to many of us if in each principal section of electrical engineering the Institution could arrange for the publication of an annual summary of new developments and problems, such summary to be prepared by someone not only familiar with published results but in touch with the work being done by such bodies as the British Engineering Standards Association, the British Electrical and Allied Industries Research Association and the like. Such a summary would, I think, be of particular value to the younger members. The practice of electricity supply, though still changing, is in many respects becoming stereotyped, and there is a tendency for the young engineer introduced to a large and complicated supply organization to assume that existing practice is the final development. It would be unfortunate if this point of view were to lead our younger members to neglect their inventive faculties, and I feel that an annual summary such as I have referred to would prove a beneficial stimulus.

Finally, I should like to refer to the question of the relationship of supply undertakings to the public, and the necessity for making clear to the public the reasons for what are often regarded as being extraordinary tariffs. It is difficult for many non-technical people to understand why a power supply and a lighting supply should differ to such a great extent in price, and the feeling that its mystery is probably a cloak for unfair discrimination is very likely to follow. We have seen recently an agitation against the "therm" basis of charging for gas, an agitation based largely on suspicion generated in the public mind because of its unfamiliarity. To any engineer who has considered the matter, the method of charging is fully justifiable, and I have noticed with pleasure the almost complete abstention on the part of the electrical industry from the campaign against the gas companies. One should, however, learn a lesson from the gas engineers' tribulations and endeavour to make clear to the public beforehand why any particular form of tariff is adopted, so that public confidence may not be lost.

This problem of equitable tariffs becomes of more importance as a supply is given over wider and less thickly populated areas. The Hopkinson basis of charges was a sufficient approximation for supply in a densely populated area, but no tariff based only on a demand charge plus a unit charge can equitably be made to fit all the circumstances in an area including town and country districts. It is necessary to declare frankly that the cost of distribution must make the charges for electricity higher in rural districts, and I think that the whole industry would be helped by a general discussion of this subject.

The work of the Institution and the Electrical Development Association in this respect is helpful, and we are, as an industry, fortunate in having the Electricity Commissioners to stand between us and an uninstructed agitation such as has been directed against the gas industry.

Progress in supply, whether under the management of a company or a municipality, can only be maintained subject to the essential economic condition of a fair return on capital and a reasonable margin to permit developments to be made by research or enterprise, so that the industry may be kept in the forefront of progress and be active and healthy enough to meet changed conditions in the interests of all concerned.

I believe that any concerted action of the industry has been much retarded by the antagonism which has existed in the past between various sections. I am glad to think that the work of the Electricity Commissioners in the co-ordination of supply, the avoidance or adjustment of overlapping powers, and the general and wide supervision which they have of the developments of electricity supply, has already done good, and that the settlement at an early date of the respective spheres of operation and the association together of electricity undertakings will permit both municipal and company engineers to co-operate as never before, without feeling that political advantage will be taken of their mutual confidence.

Many of these problems are in particular for the younger men of our industry to solve; their solution is necessary not only for the prosperity of the electricity supply industry, but in the interests of the country as a whole.

In recent years the industry has been relatively prosperous; it can only remain so by an appreciation of national needs, by hard work and by close co-operation on the part of all concerned.

---

# EAST MIDLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By William Pearson, Associate Member.

(Extract *from Address delivered at* Loughborough, 10*th October*, 1922.)

The changes which take place gradually among our daily associations tend to pass unnoticed, and it is well sometimes to attempt to realize the changes over a considerable period to determine whether the altered circumstances necessitate a new attitude towards them. As a rule these scarcely perceived changes of conditions will have resulted in an unconscious adjustment, but one inadequate to make the best of the new situation.

The genius of the British people is individualistic, and this quality, with the self-reliance and initiative associated with it, was entirely advantageous while the electrical industry was in the experimental stage. But when an industry reaches the stage of quantity production of articles of established types, the advantage tends to lie with the large manufacturing corporations which are characteristic of other countries. The remedy may be in similar large aggregations of capital and manufacturing plant, but (despite some successful examples of this kind) I believe that the engineering industry of this country will continue to be largely in the hands of companies of smaller size. The alternative is to be found in co-operative action to secure for the common good those advantages which cannot be efficiently attained by the isolated efforts of individual firms. There is also a large sphere in which the user could and should co-operate with the manufacturer for the good of the industry as a whole. It is with the idea that such co-operation should be more deliberately encouraged that I am taking this opportunity to call attention to some of the forms of co-operation which have already emerged.

Co-operation is the chief condition of progress in human society. The stimulus of competition is valuable only in so far as it leads to co-operation, and apart from this result its benefits are short-lived. Unrestricted competition results in the inefficient use of the ability employed in the industry as a whole, in crippled financial resources, and in deterioration of the product. In the world of sport everyone realizes that combination is the first essential, and there is no doubt that if, in industry, means could be found to secure whole-hearted co-operation between labour, capital and management, production would be enormously increased. Much might be said with regard to the efforts made during the past few years to secure such co-operation, but I propose to limit my remarks to the benefits resulting from co-operation between the manufacturers engaged in the engineering industry and those who represent the purchaser of the product.

This Institution has taken a leading part in one matter, not of a technical character, which will serve as an illustration—I refer to General Conditions of Contract. In the past, some of those acting on behalf of purchasers regarded the contractor not as an ally in securing the achievement of the purpose of the contract, but as an opponent to be taken at a disadvantage by the aid of very one-sided General Conditions. The position became so intolerable that in 1911 a number of manufacturers came together and agreed to insist upon three protective clauses being inserted in all contracts. Out of such action developed the British Electrical and Allied Manufacturers' Association, which has since standardized sets of general conditions applicable to all kinds of contracts and fair to both parties. But the work of the Institution in producing its more elaborated Model General Conditions of Contract in 1912 (with subsequent revisions) owes its value to the fact that it represents collaboration between all the interested parties. The use of these conditions not only removes the cause of much friction, but also saves the almost incredible amount of time which previously was wasted in the study of conditions that differed in almost every contract. In this matter the engineers appear to be pioneers, and the Federation of British Industries, which is at present investigating the possibility of producing general conditions applicable to industry generally, will probably find their best model in the I.E.E. Model General Conditions of Contract.

The revision of the I.E.E. Wiring Rules, which is at present in progress, is another example of an important matter in which all the organizations interested are participating.

Other collaborations of similar type but more limited scope are those between the Incorporated Municipal Electrical Association and the British Electrical and Allied Manufacturers' Association, dealing with standard schedules of guarantee and performance, etc., in relation to turbo-generator and condensing-plant contracts.

In passing, it should be noted that the Institutions themselves represent a form of co-operation between individual engineers, and that the need for further co-operation has led to the proposal of a Joint Council for the four premier Institutions, and to an endeavour to form an Association of British Engineering Societies to co-ordinate the work of a large number of other technical organizations.

The function of the engineer may be defined as "the economy of human effort," and in support of this one need only mention transport by land and sea, or the application of power to all kinds of manufacture. Yet it is probable that the number of non-producers in engineering is at least as large proportionately as in other industries. There seems to be no immediate prospect of any serious reduction in the large army of workers engaged in the distribution of goods made by other people, but a small effort in this direction is the co-operative publicity work which is the function of the British Electrical Development Association, a development of the Heating and Cooking Committee of this Institution, and the result of the collaboration of seven other Associations with the Institution.

The most important of these endeavours to secure efficiency in the industry by the combined efforts of all interested parties relate, however, to research and standardization, and I wish to direct your attention particularly to these subjects.

(Mr. Pearson then referred to the research work fostered by the Committee of the Privy Council for Scientific and Industrial Research, and described in detail the organization and work of the British Electrical and Allied Industries Research Association. He also described the origin, purpose and methods of the organizations concerned with standardization, i.e. the British Engineering Standards Association and the International Electrotechnical Commission. He quoted the official B.E.S.A. statement that "Industrial standardization has for its main objects the elimination of the waste of time and material involved in the production of a multiplicity of sizes and qualities for one and the same purpose, the fixing of dimensions of component parts where interchangeability is essential, the setting up of standards of performance whereby comparisons can be made with equity, and the defining of attainable quality of material." He indicated various kinds of standardization fulfilling these different objects, and then made special reference to the Rating of Electrical Machinery, describing the recent revision of British Standard Specification No. 72 as being the most important in relation to electrical engineering. He showed how the several Specifications shortly to be issued would adequately meet the needs of the industry, which the superseded document failed to do, and urged it as a duty to make the fullest possible use of these Specifications when available.)

# THE PRODUCTION OF NOISE AND VIBRATION BY CERTAIN SQUIRREL-CAGE INDUCTION MOTORS.*

By F. T. CHAPMAN, D.Sc., Member.

(*Paper received 3rd April, 1922.*)

SUMMARY.

(1) A suggestion is made that the high-pitched notes emitted by some induction motors are due to a side-pull arising from an unsymmetrical field which may be produced when certain numbers of rotor slots are used.
(2) A simple case is first considered and the dissymmetry shown.
(3) and (4) The forces produced are indicated and their effects considered.
(5) The field is analysed and found to include pairs of components, such that in each pair the numbers of poles differ by two. The interferences between such pairs of fields produce the effects observed.
(6) An elementary investigation is made which gives an expression for the frequency of the note produced.
(7) Illustrative examples are considered.
(8) The principle is extended.
(9) A more general investigation is made.
(10) A rule is developed for determining what numbers of rotor slots should be avoided
(11) Some experimental results are given.

## (1.)

Induction motors with squirrel-cage rotors usually have excellent characteristics as regards efficiency, power factor and robustness, while a high starting torque is not expected of them, in general. The rotor is extremely simple, but in spite of this simplicity it presents one or two minor, though intricate, problems in connection with the choice of the number of slots. In order to secure a high power factor at full load and a large pull-out torque it is desirable to employ a large number of slots per pole, say 10 or more, but such a rotor may exhibit a tendency to crawl at or about certain sub-multiples of synchronous speed, viz. in the case of a three-phase motor, 1/7th, 1/13th, etc., of full speed. This tendency to crawl can be sufficiently prevented (*a*) by adopting suitable fractional-pitch windings in the stator, and (*b*) by skewing the rotor slots through one stator slot-pitch. There are cases, however, where these remedies cannot be applied and where crawling is guarded against by using a suitably chosen number of slots less than the number in the stator. Such rotors have the additional advantage that they are cheaper to construct than those having larger numbers of slots.

Considerable care is necessary in choosing the number of slots in the latter case, as such rotors are liable to be very noisy in starting and on load, they may exhibit a tendency to crawl at speeds higher than those mentioned above, and they may give rise to serious vibration. Experienced designers are familiar with certain numbers of slots which are safe, but, so far as the author knows, the matter has never been very fully investigated nor have any reliable rules been published. Most manufacturers have trouble from this source from time to time, but direct experimental investigation is not possible on account of the large expense involved in testing a sufficiently great number of combinations of numbers of poles, and of rotor and stator slots. A motor which has the defects mentioned may produce a fairly high-pitched musical note at speeds within a certain range, and the intensity of the sound may reach a maximum near the middle of the range. In some cases there are several noisy speed-ranges and full-load speed may come within one of them, although a motor which is very noisy at one point during the starting period may operate quite quietly at full speed. When the maximum effect is felt at some speed during the starting period, the vibration may be sufficiently severe to introduce a considerable retarding torque due to friction at the bearings and also, perhaps, to the currents induced in the rotor by its peculiar motion in the field, and the remaining torque may be zero or insufficient to accelerate the machine further.

These effects are probably due to unbalanced magnetic fields, arising as indicated below, which produce rotating forces similar to those caused by mechanical unbalance; the speed of rotation of these forces is much higher than that of the rotor itself, so that the critical speed of the rotor is reached and exceeded even in moderate-speed machines.

## (2.)

It is convenient to commence by studying a definite, simple case and we will consider a rotor with five slots acted on by a four-pole, sine-shaped rotating field. We shall neglect the slot openings and assume that the rotor is surrounded by a uniform air-gap.

Fig. 1 shows the relative positions of rotating field and rotor conductors at a certain instant. The teeth are numbered and the arrow indicates the direction of motion of the field with respect to the rotor, the latter being supposed at rest. Positive ordinates indicate flux entering the rotor. It is clear that all the rotor conductors will experience the same virtual E.M.F. and they will all have the same inductance and resistance, hence the virtual current and the angle of lag will be the same for all. The phase difference between the E.M.F.'s or currents in successive conductors is $4\pi/5 = 144°$. The vector diagram in Fig. 2 refers to the same instant as Fig. 1, and the full lines represent the E.M.F.'s in the rotor conductors. The vector marked (5, 1) refers to the conductor in the slot between tooth No. 5 and tooth No. 1. In this investigation we shall neglect the resistance of the conductors, so that the current will lag 90° behind the E.M.F. in all cases. On this assumption the current vectors are shown in Fig. 2 by broken lines.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

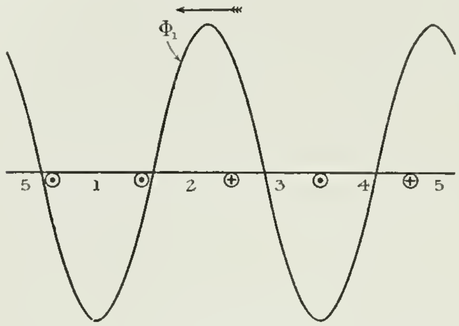


FIG. 1.

Now, the conductors are short-circuited at each end by rings, which rings are not connected together by any other path, therefore the sum of the five currents must be zero at every instant. This means that the vectors representing them must form a closed polygon when taken in the same order as the slots. This polygon is drawn in Fig. 3 and is so numbered that the vector (5, 1) represents the current in the conductor between tooth No. 5 and tooth No. 1, and so on. These rotor currents produce a magnetic field which combines with the original four-pole field and produces a very irregular resultant. We shall assume that the effects of saturation and of the slot openings can be neglected, and in the first place we shall examine the form of the field which the rotor currents would produce if they acted alone.

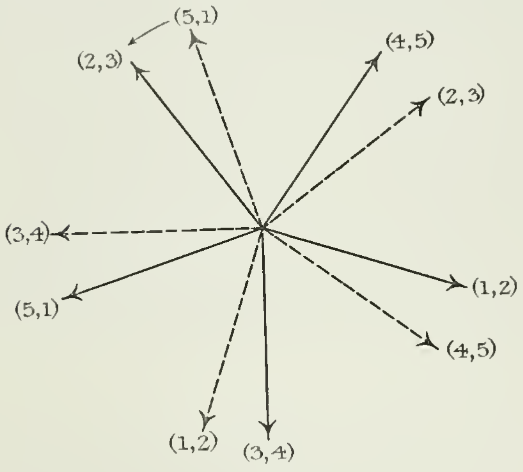


FIG. 2.

It is a well-known proposition that the M.M.F. acting on the air-gap opposite tooth 5 differs from that acting opposite tooth 1 by the M.M.F. due to the current in conductor (5, 1); hence, if 0 be the centre of the circumscribing circle in Fig. 3, the vectors (0, 1), (0, 2), (0, 3), etc., will represent the maximum ampere-turns acting on the air-gap opposite teeth Nos. 1, 2, 3, etc., respectively, to the same scale as (5, 1), (1, 2), etc., represent the maximum current per conductor. This follows because the vector (5, 1) is the difference between the vectors (0, 5) and (0, 1), and because the algebraic sum of the instantaneous values of the fluxes in all the teeth must be zero at every instant. With the aid of Fig. 3 we can draw the stepped curve of Fig. 4 (abcdefghkl) which shows the distribution of the field, $\Phi_2$, due to the rotor currents at the instant when the flux in tooth 1 is at its maximum value. It will be seen that a kind of four-pole field is produced which satisfies the condition that the total flux entering the rotor is equal to the total flux leaving it.

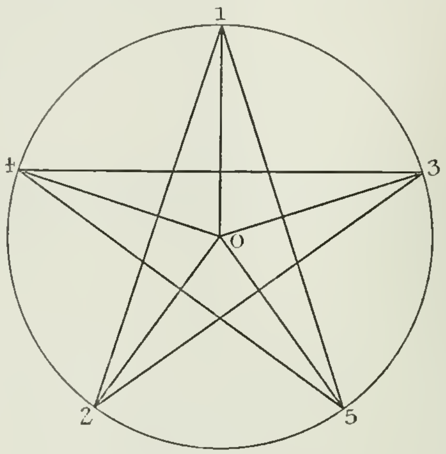


FIG. 3.

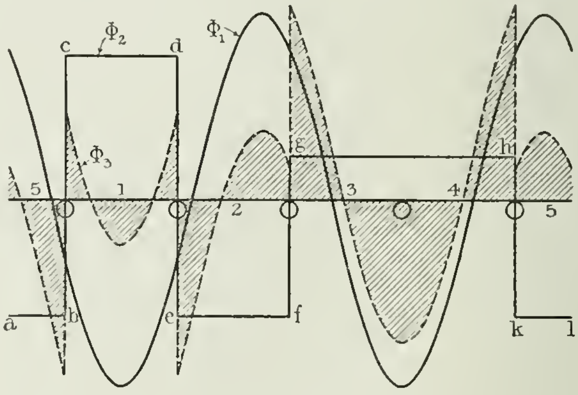


FIG. 4.

The curve $\Phi_1$ shows the position of the main flux wave at this instant. The curve $\Phi_3$ which bounds the shaded areas is obtained by adding together at each point along the rotor surface the ordinates of curves $\Phi_1$ and $\Phi_2$. The values of the rotor currents and fluxes have been calculated on the assumption that the end leakage may be neglected. The formulæ employed were those given by the author in a paper on "The Air-gap Field of the Induction Motor," * and they indicate that the maximum height of the stepped curve is 0·757 times the height of the $\Phi_1$ curve. A useful check on this figure is provided by the fact that, since the rotor conductors are assumed to have no resistance, the net flux traversing any tooth must be zero at every instant, a condition which the curve $\Phi_3$ fulfils.

### (3.)

Now the force with which any element of the rotor surface is attracted towards the stator is proportional to the square of the flux density at that point. The circle in Fig. 5 represents the rotor of the previous figures, the conductors being shown and the teeth numbered. Outside the circle radial lines have been drawn, the lengths of which are proportional to the squares of the resultant densities ($\Phi_3$) shown in Fig. 4.

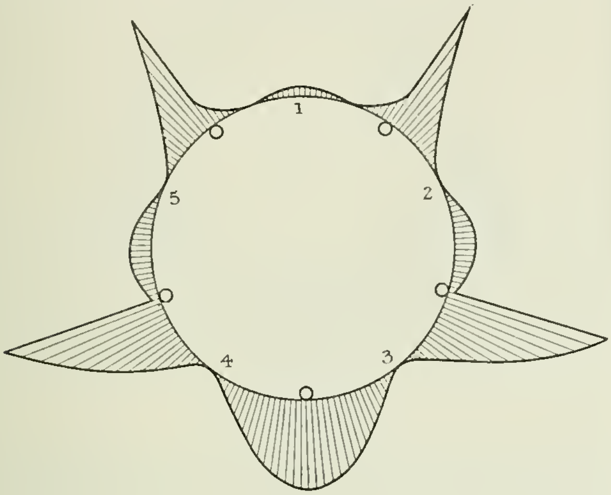


FIG. 5.

It is clear from this diagram that the rotor experiences a resultant force directed radially outwards through the centre of slot (3, 4).

Fig. 6 has been drawn to show the flux distribution 1/10th cycle later when $\Phi_1$ has moved through 1/20th revolution and the vectors of Figs. 2 and 3 have moved through 1/10th revolution. The resultant field is similar to that of Fig. 4, except that it is moved one slot to the right and reversed in sign. If a new figure corresponding to Fig. 5 were drawn for this case it would be found that the resultant force had the same value as before, but was now directed outwards between tooth No. 4 and tooth No. 5, hence in 1/10th cycle its direction has turned through 1/5th revolution. Further diagrams drawn in the same way would show that the force vector makes two revolutions per cycle and therefore rotates four times as fast as $\Phi_1$, relatively to the rotor.

### (4.)

This unbalanced force tends to bend the shaft of the rotor and, under steady conditions, the plane of the neutral axis will rotate at the same speed in space as the unbalanced force; this speed is quite different from the speed of rotation of the rotor, if any. The shaft being bent, the air-gap is reduced on one side and an increased unbalanced magnetic attraction is produced, which is added to the original disturbing force, and further, since the centre of gravity of the rotor is whirling with the neutral axis in a circle, a centripetal mass-acceleration is required to maintain the motion. Steady motion is obtained when the shaft is bent to such an extent that the elastic forces set up by the bending are just sufficient to balance the magnetic attraction and to provide the requisite mass-acceleration. It should be noted that such steady conditions cannot exist while the rotational speed of the rotor is changing, because the frequency of the forces brought into play is changing continuously.

The forces acting on the stator and rotor due to magnetic unbalance are equal and opposite, and therefore are balanced if the motor is regarded as a whole, but it is otherwise with the mass-acceleration, which leads to reactions at the bearings that are transmitted to the foundations, producing the same effects as regards noise and vibration as if the rotor were mechanically out of balance and were rotating at the speed at which it now whirls. We shall see later that conditions may exist in a motor which cause the frequency of these forces to be that of a high-pitched musical note, and therefore comparatively small forces (i.e. small deflections) will cause a loud noise. It will also be obvious from the dynamics of the problem that with a given initial disturbing force there will be a certain speed of rotation of this force at which the deflection of the shaft becomes unstable and stator and rotor may come into contact with one another. From the examples given below we shall see that, as the rotor accelerates, the speed of the disturbing force varies over a very wide range, and the critical whirling speed to which we have just referred (which is practically identical with the mechanical critical speed) may be included within this range; the vibration may then be so severe that further acceleration is prevented. Thus we get a crawling speed of a new kind, which is necessarily accompanied by loud noise and vibration.

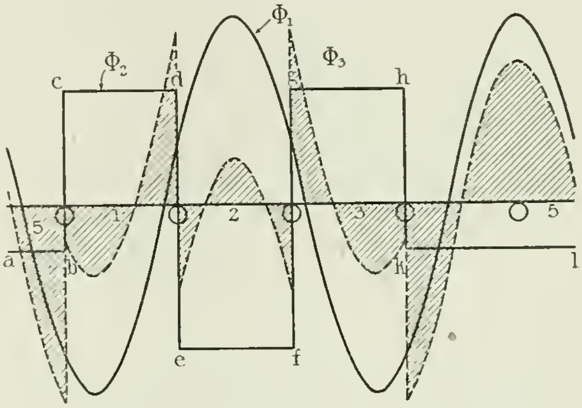


FIG. 6.

The action of the main magnetic field under these

---

* *Electrician*, 1916, vol. 77, p. 663.

circumstances is somewhat obscure, since the presence of the closed squirrel-cage winding prevents rapid changes in the flux distribution, which might otherwise be caused by the whirling. It may be expected, however, to flatten out the resonance curve to a considerable extent and to damp the whirling. It will be clear that if two motors which are otherwise identical have shafts with different degrees of stiffness, the one with the more rigid shaft is less likely to give trouble than the other. Any looseness in the bearings, between the rotor and the shaft or between the stator and its housing, would accentuate the effects here discussed. It may be possible for a given combination of stator and rotor slots to be troublesome in one case and to have little effect in another.

### (5.)

The method of investigation which has been given in Section 2 is too laborious for general use, and a further analysis is necessary in order to establish rules to indicate how these effects may be avoided.

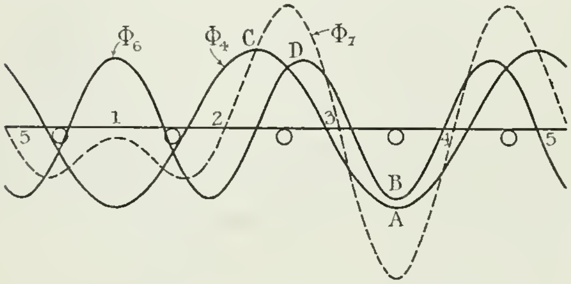


FIG. 7.

A useful light is thrown on the phenomenon if we apply Fourier's analysis to the fields shown in Figs. 4 and 6. In the paper * referred to above, the author has shown that if an inducing field having $p$ poles acts on a squirrel-cage rotor winding with $G$ conductors the fields produced by the rotor currents can be resolved into a series of fields, each of which has $cp$ poles, and may rotate in the same direction as the original field, or in the opposite direction with respect to the rotor. The possible values for $c$ form an infinite series and the general term is given by the expression

$$c = \frac{2Gd}{p} + 1 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $d$ is any positive or negative integer. Those fields for which $c$ is negative rotate in the opposite direction to the original field, the others in the same direction. The speeds of the fields are such that they all produce E.M.F.'s of the same frequency, in phase with one another, in any rotor conductor.

Formula (1) can be written

$$cp = 2Gd + p \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The amplitude of any one of these fields is equal to

$$\frac{2G \sin (cp\pi/2G)}{cp\pi} \times y$$

where $y$ is the maximum density in the air-gap opposite any tooth, as determined from such a vector diagram as that given in Fig. 3.

If we consider the case of Section 2 in which $G = 5$ and $p = 4$, and substitute successively in Equation (2) the following values for $d$, viz. 0, $-1$, $+1$, $-2$, $+2$, etc., we get the following as the numbers of poles in the series of multiple fields that are present,

$$cp = 4, \ -6, \ 14, \ -16, \ 24, \text{ etc.}$$

The important point about this series is that it consists of a number of pairs of oppositely rotating fields in which the numbers of poles differ by two, thus (4, $-$ 6), (14, $-$ 16), etc.

In Fig. 7 the curve $\Phi_4$ represents the difference between $\Phi_1$ and the four-pole component of $\Phi_2$, a flux wave which moves, like $\Phi_1$, from right to left; $\Phi_6$ represents the six-pole component of $\Phi_2$ and moves from left to right. $\Phi_7$ represents the resultant of these two fields at a certain instant, and the corresponding force diagram is shown in Fig. 8. Figs. 7 and 8 show the characteristic feature of the resultant field produced by combining a $p$-pole field with a $(p \pm 2)$-pole field, viz. that there is a strong zone the centre of which is immediately opposite to that of a weak zone, which leads to an unbalanced magnetic pull. This force can be represented by a radial vector rotating about the axis of the rotor.

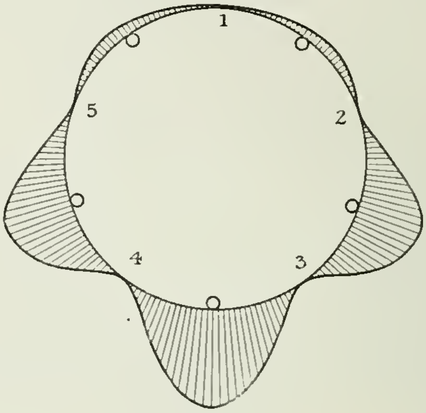


FIG. 8.

If a $p$-pole field be combined with a $(p + x)$-pole field, where $x = 4, 6, 8, 10$, etc., there will be $x/2$ strong and $x/2$ weak zones distributed regularly round the periphery of the rotor, and the forces will constitute a balanced system. It is only when $x = 2$ that unbalanced forces arise.

### (6.)

The speed at which the force vector rotates can be determined in the following manner. Suppose we have a $p_1$-pole field rotating at $n_1$ revs. per sec., and a $p_2$-pole field rotating at $n_2$ revs. per sec. If $p_2 = p_1 + 2$, then interference effects will be produced as shown above. When a crest of the $p_1$-pole field coincides with a crest of the $p_2$-pole field, as shown in Fig. 7 at A and B, the force vector is directed outwards through the corresponding point on the rotor, viz. slot (3, 4). We will take a movement from right to left as positive. At

---

* Loc. cit.

a certain instant, earlier or later than that of Fig. 7 according to the direction of relative motion of the two fields, the crests C and D will coincide and the force vector will have moved to this new point of coincidence. The speed of the $p_2$-pole field with respect to the $p_1$-pole field is $(n_2 - n_1)$ revs. per sec. Relatively to the $p_1$-pole field the force vector will have moved from A to C, i.e. through $1/p_1$th of the circumference, while the $p_2$ field moves through $(1/p_1 - 1/p_2)$th of the circumference, hence the velocity of the force vector relative to the $p_1$-pole field is greater than the relative velocity of the $p_2$-pole field in the ratio

$$1/p_1 : (1/p_1 - 1/p_2)$$

therefore the speed of the force vector relative to the $p_1$-pole field is

$$\begin{aligned}(n_2 - n_1) &\times \frac{1/p_1}{1/p_1 - 1/p_2}\\ &= \frac{(n_2 - n_1)p_2}{p_2 - p_1}\\ &= \tfrac{1}{2}[(n_2 - n_1)p_2] \quad . \quad . \quad . \quad . \quad (4)\end{aligned}$$

Now the speed of the $p_1$-pole field is $n_1$, so that the speed of the force vector in space is

$$\begin{aligned}n_1 &+ \tfrac{1}{2}[(n_2 - n_1)p_2]\\ &= \tfrac{1}{2}[n_2p_2 - n_1(p_2 - 2)]\\ &= \tfrac{1}{2}(n_2p_2 - n_1p_1) \quad . \quad . \quad . \quad . \quad (5)\end{aligned}$$

If either of these fields is produced by the direct magnetizing effect of the stator currents, its speed is known from the relation $np = 2f$, where $f$ is the primary frequency; but if one or both arise from rotor currents the speeds must be calculated as follows. Suppose a $p_4$ field is produced by rotor currents which are induced by a $p_3$ stator field, then

$$(\pm)p_4 = 2Gd + p_3 \quad . \quad . \quad . \quad . \quad (6)$$

If the speed of the $p_3$ field is $n_3$ and that of the rotor $n_0$, the frequency of the rotor currents under consideration is

$$(n_3 - n_0)p_3/2 \quad . \quad . \quad . \quad . \quad (6a)$$

$n_3$ must here be given its proper sign, whilst $p_3$ is taken as a positive quantity.

(The difference between a positive and a negative frequency is expressed in the difference in phase sequence of the currents in the rotor bars. For example, in order to produce the same frequency in this sense, the four-pole and six-pole fields of Fig. 7 must rotate in opposite directions with respect to a five bar rotor, whereas if both rotated in the same direction the frequencies of the E.M.F.'s produced would differ in sign.)

The speed of the $p_4$ field relative to the rotor is such that the frequency of the E.M.F.'s which it induces in the rotor conductors is the same as the frequency due to the $p_3$ field, i.e.

$$(n_4 - n_0) \times (\pm)\, p_4 = (n_3 - n_0)p_3 \quad . \quad . \quad (7)$$

hence $$n_4 = n_0 + (n_3 - n_0)p_3/(\pm)p_4 \quad . \quad . \quad . \quad (8)$$

or, to avoid ambiguity of sign, we may write

$$\begin{aligned}n_4 &= n_0 + \frac{(n_3 - n_0)p_3}{2Gd + p_3}\\ &= \frac{2Gdn_0 + n_3p_3}{2Gd + p_3} \quad . \quad . \quad . \quad . \quad (9)\end{aligned}$$

$n_4$ may be either positive or negative, and when required for substitution in Equation (5) as $n_1$ or $n_2$ it must always be associated with its proper sign; on the other hand, when $p_4$ is used in this equation as $p_1$ or $p_2$, it must be taken as a positive quantity; the examples given in Section 7 will help to make this point clear.

Since the force acting on each element of the rotor surface depends on the total induction density there, this method of singling out two components of the field and considering them apart from the rest requires some justification; it explains the phenomena clearly and correctly, but it does not constitute a sufficiently rigorous treatment of the problem. A more general treatment is given in Section 9, where it is shown that an unbalanced force can only arise when there are component fields with numbers of poles differing by two, and that the magnitude of this force is proportional to the product of the amplitude of these two components.

### (7.)

Some numerical examples will serve to illustrate the matter.

*Example* (1). *A four-pole, 50-period three-phase motor has a squirrel-cage rotor with 19 slots; the fifth multiple field of this machine has 20 poles and runs backwards at a speed which is one-fifth of that of the main field, i.e. at − 5 revs. per sec.*—From Equation (2) we see that the rotor currents induced by this field produce a series of fields the numbers of poles in which are

20, − 18, 58, − 56, and so on,

a series of pairs of numbers differing by two in each case. We will consider the first pair in which

$$p_3 = 20 = p_2, \text{ and } p_4 = 18 = p_1, \ (d = -1)$$

*Case* (*a*).—If the rotor is stationary we have $n_0 = 0$

$$n_3 = n_2 = -5, \text{ and } n_4 = n_1 = \frac{0 - 5 \times 20}{-18}$$

[from Equation (9)]

$$\begin{aligned}n_2p_2 &= -5 \times 20 = -100\\ n_1p_1 &= +5 \times 20 = +100\end{aligned}$$

hence the speed of the force vector, by Equation (5), is

$$\frac{-100 - 100}{2} = -100 \text{ revs. per sec.}$$

*Case* (*b*).—At synchronism, $n_0 = 25$ revs. per sec.

$$\begin{aligned}n_3 &= n_2 = -5\\ n_4 &= n_1 = \frac{-2 \times 19 \times 25 - 5 \times 20}{-18} = \frac{1\,050}{18}\end{aligned}$$

hence the speed of the force vector is

$$\frac{-5 \times 20 - 1\,050}{2} = -575 \text{ revs. per sec.}$$

This speed corresponds to a fairly high musical note. Between standstill and full speed the force vector will probably have passed through the critical speed of the rotor.

*Example* (2). *A four-pole, 50-period three-phase motor* *has a squirrel-cage rotor with 29 slots. The seventh multiple field of this machine has 28 poles and its speed is* + 3·57 *revs. per sec.*—The numbers of poles in the components of the field set up by the rotor currents induced by the seventh stator field are, by Equation (2)

$$28, \ -30, \ 86, \ -88, \text{ etc.}$$

*Case* (*a*).—When the rotor is stationary, $n_0 = 0$. Considering the first pair of fields, we have

$$p_3 = p_1 = 28; \ p_4 = p_2 = 30,$$
$$n_3 = n_1 = 3{\cdot}57,$$
$$n_4 = n_2 = \frac{0 + 3{\cdot}57 \times 28}{-30}, \text{ (since } d = -1)$$

The speed of the force vector is

$$\frac{-3{\cdot}57 \times 28 - 3{\cdot}57 \times 28}{2} = -100 \text{ revs. per sec.}$$

*Case* (*b*).—At synchronism, $n_0 = 25$ revs. per sec.

$$n_3 = n_1 = 3{\cdot}57$$
$$n_4 = n_2 = \frac{-58 \times 25 + 3{\cdot}57 \times 28}{-30}$$
$$= \frac{1\,350}{30}$$

The speed of the force vector is

$$\frac{1\,350 - 3{\cdot}57 \times 28}{2} = 625 \text{ revs. per sec.}$$

Between standstill and synchronism there is obviously some speed of the rotor at which the force vector is stationary. This speed can be determined from the equations given above, and is 3·45 revs. per sec. The magnitude of the force at this speed, however, is extremely small.

## (8.)

In the two cases considered in Section 7 the rotor currents themselves give rise to pairs of fields which interfere with one another and produce the magnetic "beats" which cause the rotating side pull, but there are cases of another kind in which a field produced by the stator currents interferes with an entirely independent one produced by the rotor currents. For instance, if a four-pole, three-phase motor has a squirrel-cage rotor with 25 slots, the currents induced in the rotor bars by the main field will produce a complex field with components having

$$4, \ -46, \ +54, \text{ etc., poles.}$$

The − 46 field interferes with the 11th multiple field of the stator which has 44 poles. If the stator should have 24 slots the 11th field would be very important, especially if the slots were open rather wide, in which case its amplitude at full load might exceed that of the main field. On the other hand, the currents induced in the rotor winding by the 11th stator field produce a complex field the components of which have

$$44, \ -6, \ 94, \ -56, \text{ etc., poles.}$$

The (− 6)-pole field is the most important of this series; its amplitude is greater than that of the 44-pole field, and it produces interference effects with the main field of the motor. The force vectors corresponding to these two sets of "beats" rotate at the same speed, but in general they differ in magnitude and in phase and produce a resultant. If the frequency of supply were 50 periods per sec. and the motor were running with 20 per cent slip, the speed of the force vectors would be 560 revs. per sec.

A 25-slot rotor in a four-pole motor produces a large number of other sets of interfering fields and so has a great capacity for producing noise.

## (9.)

### General Expression for the Radial Forces acting on a Rotor.

Let the circle of Fig. 9 represent an end view of the periphery of a rotor, round which a complex field exists. In a perfectly general case the induction density at any point P on the surface of the rotor is given by the expression

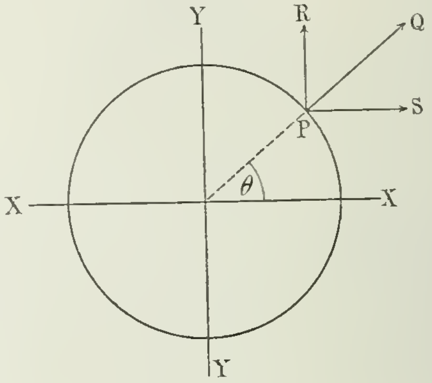


Fig. 9.

$$A \sin(\theta + a) + B \sin(2\vartheta + b) + C \sin(3\vartheta + c) + \ldots$$

The radial force $PQ$ acting on an element of the surface measuring $\delta\theta$ tangentially and of unit length axially is given by the expression

$$K\,\delta\theta[A \sin(\theta + a) + B \sin(2\theta + b) + C \sin(3\theta + c) + \ldots]^2$$

where $K$ is a numerical coefficient.

In order to examine to what extent the forces on all the elements of the surface are balanced we will resolve $PQ$ into its components

$$\begin{aligned} PR &= PQ \sin\theta \\ &= K[A \sin(\theta + a) + B \sin(2\vartheta + b) + \ldots]^2 \sin\theta\,\delta\theta \quad . \quad (10) \end{aligned}$$

and

$$\begin{aligned} PS &= PQ \cos\theta \\ &= K[A \sin(\theta + a) + B \sin(2\vartheta + b) + \ldots]^2 \cos\theta\,\delta\theta \quad . \quad (11) \end{aligned}$$

*Case* (*a*). *Permeance of air-gap uniform.*—$K$ is now a constant and by integrating expression (13) between $\theta = 0$ and $\theta = 2\pi$ we get a value for the unbalanced force in the direction of the $y$-axis, while the integration of (14) gives the unbalanced force in the direction of the $x$-axis.

These integrations furnish a first series of terms such as

$$K\int_0^{2\pi} N^2 \sin^2 (\nu\theta + n) \sin\theta \, d\theta$$

and $$K\int_0^{2\pi} N^2 \sin^2 (\nu\theta + n) \cos\theta \, d\theta, \text{ respectively}$$

the values of which are all zero, and a second series of terms such as

$$K\int_0^{2\pi} 2MN \sin (\mu\theta + m) \, . \sin (\nu\theta + n) \sin\theta \, d\theta$$

and

$$K\int_0^{2\pi} 2MN \sin (\mu\theta + m) \, . \sin (\nu\theta + n) \cos\theta \, d\theta, \text{ respectively,}$$

where $\nu$ is greater than $\mu$.

The first of these becomes

$$NMK\int_0^{2\pi} \cos [(\mu - \nu)\theta + (n - m)] \sin\theta \, d\theta$$
$$- NMK\int_0^{2\pi} \cos [(\mu + \nu)\theta + (n + m)] \sin\theta \, d\theta$$

which develops into

$$\tfrac{1}{2}NMK\int_0^{2\pi} \sin [\theta + (\mu - \nu)\,\theta + m - n] d\theta$$
$$- \tfrac{1}{2}NMK\int_0^{2\pi} \sin [\theta - (\mu - \nu)\theta - (m - n)] d\theta$$
$$- \tfrac{1}{2}NMK\int \sin [\theta + (\mu + \nu)\theta + n + m] d\theta$$
$$+ \tfrac{1}{2}NMK\int_0^{2\pi} \sin [\theta + (\mu + \nu)\theta - m - n] d\theta$$

Since $\mu$ and $\nu$ are both positive integers and $\nu$ is greater than $\mu$, the last three terms are all zero. The first term is also zero except in the one case where $\nu - \mu = 1$; its value is then

$$PR = \pi NMK \sin (m - n)$$

Similarly the cosine component, $PS$, is

$$\pi NMK \cos (m - n)$$

when $\nu - \mu = 1$, and is zero in all other cases. The resultant unbalanced force, $PQ$, is $\pi MNK$ and is inclined to the $x$-axis at an angle $(m - n)$.

Thus we see that if the actual field can be resolved into components two of which have numbers of poles, $2\mu$ and $2\nu$, which differ by 2, these two fields will cause a resultant radial force to act on the rotor. In a perfectly general case it is conceivable that there might be a number of such pairs of fields, the effects of which might cancel one another, but in the induction motor such pairs only occur in the special circumstances investigated above.

In the induction motor the components of the field are rotating at various speeds, and therefore $n$ and $m$ are functions of the time. If we suppose the $\mu$ field to be rotating with angular velocity $\omega_1$, and the $\nu$ field with angular velocity $\omega_2$, then

$$m = - \mu\omega_1 t + m'$$

and $$n = - \nu\omega_2 t + n'$$

hence $$m - n = m' - n' + (\nu\omega_2 - \mu\omega_1)t \quad . \quad . \quad (12)$$

The instantaneous components of the unbalanced force are

$$PR = \pi NMK \sin [(\nu\omega_2 - \mu\omega_1)t + (m' - n')] \quad . \quad (13)$$

and $$PS = \pi NMK \cos [\nu\omega_2 - \mu\omega_1)t + (m' - n') \quad (14)$$

which indicate a constant force of magnitude proportional to the product of the amplitudes of the two fields, applied to the rotor in a direction which rotates with an angular velocity of $(\nu\omega_2 - \mu\omega_1)$ radians per sec.

Each pair of fields with numbers of poles differing by two will produce such a rotating force, but in the practical case the resulting forces differ in magnitude and in relative position, and generally they cannot cancel one another.

The speed of the rotating force in revs. per sec. is

$$\nu\frac{\omega_2}{2\pi} - \mu\frac{\omega_1}{2\pi}$$

and, since $\nu = \frac{1}{2}p_2$ and $\mu = \frac{1}{2}p_1$, this expression is identical with Equation (5).

*Case* (*b*). *Variable permeance.*—When the permeance of the air-gap varies periodically owing to the presence of slot apertures, etc., $K$ is not constant but varies in a regular manner from a maximum to a minimum and back again to a maximum. If we suppose the effect to be due to the slot openings of the rotor only, the permeance will have $G$ maximum and $G$ minimum values. Let us consider $G$ points on the circumference at each of which the permeance will have the same value. For each point we shall have a pair of expressions such as (13) and (14) above. Taking first expression (13) and assuming $\theta$ to be measured from one of the $G$ points, we get a series of expressions for the sine components of the forces acting at the several points, such as

$$K[A \sin a + B \sin b + \ldots N \sin n \ldots]^2 \sin 0 \, . \, \delta\theta$$
$$K[A \sin (2\pi/G + a) + B \sin (4\pi/G + b) + \ldots$$
$$+ N \sin (2\nu\pi/G + n) + \ldots]^2 \times \sin (2\pi/G) \, . \, \delta\theta$$

etc.

The $(R + 1)$th expression is

$$K[A \sin (2\pi R/G + a) + B \sin (4\pi R/G + b) + \ldots$$
$$+ N \sin (2\nu\pi R/G + n) + \ldots]^2 \sin (2\pi R/G) . \, \delta\theta$$

Each of these $G$ expressions contains similar terms to those set out for the $(R + 1)$th. Expanding the $(R + 1)$th expression we obtain two series of terms such as

$$KN^2 \sin^2 (2\nu\pi R/G + m) \, . \sin (2\pi R/G) . \, \delta\theta \quad . \quad . \quad (15)$$

and

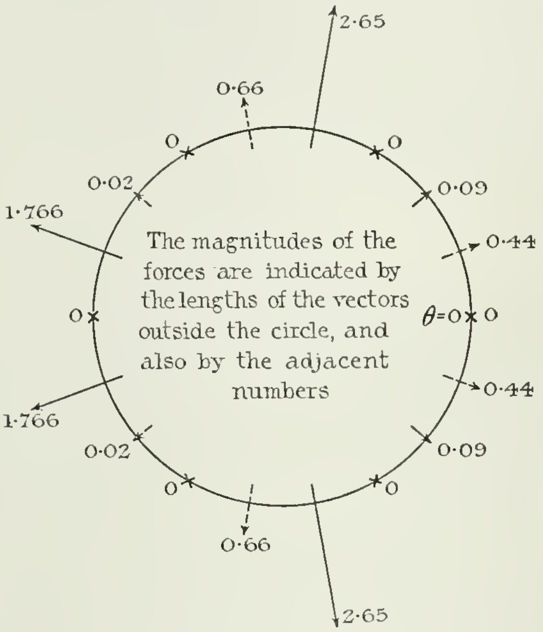
$$2KMN \sin (2\mu\pi R/G + m) \, . \sin (2\nu\pi R/G + n)$$
$$. \sin (2\pi R/G) . \, \delta\theta \quad . \quad (16)$$

When we add together the expanded expressions for all the $G$ components we find that the terms can be arranged in two classes of series. Those of the first class contain $G$ terms in $A^2$, or in $B^2$, . . . or in $N^2$, . . . similar to (15), and in each series $R$ has successive values of 0, 1, 2, . . . $(G-1)$. Those of the second class contain terms in $AB$, or $BC$, or . . . $MN$ . . . similar to (16) in which $R$ has the successive values just mentioned.

Let us consider a typical series of the first class. The general term given in (15) can be further expanded to the following form

$$\tfrac{1}{2}KN^2\,\delta\theta\big[\sin 2\pi R/G + \tfrac{1}{2}\sin\big\{(2\nu-1)2\pi R/G + 2n\big\} - \tfrac{1}{2}\sin\big\{(2\nu+1)2\pi R/G + 2n\big\}\big]$$

from which it is obvious that the sum of the series in $N^2$ is zero unless $G = (2\nu \pm 1)$, and that the sum of all the series in this class is zero unless there is at least one component field for which the number of poles is $(G \pm 1)$. Another form of this statement would be: If a component of the field has $p$ poles and $G = (p \pm 1)$ a side-pull will result from this combination, which is obviously true without further explanation.



The magnitudes of the forces are indicated by the lengths of the vectors outside the circle, and also by the adjacent numbers

Fig. 10.

Returning now to the series of the second class, the general term (16) can be expanded to the following form

$$\begin{aligned}\tfrac{1}{2}KMN\,\delta\theta\big[&\sin\big\{(\nu-\mu+1)2\pi R/G + n - m\big\}\\ &- \sin\big\{(\nu-\mu-1)2\pi R/G + n - m\big\}\\ &- \sin\big\{(\nu+\mu+1)2\pi R/G + n + m\big\}\\ &+ \sin\big\{(\nu+\mu-1)2\pi R/G + n + m\big\}\big]\end{aligned}$$

from which it is clear that the sum of the series in $MN$ is zero unless $G = (\nu \pm \mu \pm 1)$, and the sum of all the series of this class will be zero unless $G$ differs by unity from the sum or difference of the numbers of pairs of poles in any two of the component fields.

The significance of this condition is not very obvious and an example will help to make it clear. Suppose we have a field of four poles $(\mu = 2)$ with a fifth multiple of 20 poles $(\nu = 10)$, and suppose that $G = 9 (= \nu - \mu + 1)$. For the sake of simplicity we will assume that both fields have the same amplitude, so that the flux density at the $(R+1)$th point will be proportional to

$$\sin 2\pi R/G + \sin 10\pi R/G$$

The full-line vectors in Fig. 10 represent the squares of the nine values of this quantity and clearly indicate the presence of a resultant side-pull. The dotted vectors in the same figure show the values of the same quantities at points midway between the $G$ points already considered; these have been drawn on the assumption that the permeance at the second set of points is one-half that at the first set. The two sets of forces evidently produce a resultant which would not have been present if the permeance had been uniform. If other intermediate sets of points are considered it will be seen that a resultant side-pull must be produced unless the permeance at all points separated by $1/2G$ of the circumference of the rotor is the same

Returning to the expressions for the cosine terms corresponding to (15) and (16), we find that they can be expanded to

$$\tfrac{1}{2}KN^2\,\delta\theta\big[\cos 2\pi R/G - \tfrac{1}{2}\cos\big\{(2\nu+1)2\pi R/G + 2n\big\} - \tfrac{1}{2}\cos\big\{(2\nu-1)2\pi R/G + 2n\big\}\big]$$

and

$$\begin{aligned}\tfrac{1}{2}KMN\,\delta\theta\big[&\cos\big\{(\nu-\mu+1)2\pi R/G + n - m\big\}\\ &+ \cos\big\{(\nu-\mu-1)2\pi R/G + n - m\big\}\\ &- \cos\big\{(\nu+\mu+1)2\pi R/G + n + m\big\}\\ &- \cos\big\{(\nu+\mu-1)2\pi R/G + n + m\big\}\big]\end{aligned}$$

Taking first the case of $G = 2\nu + 1$, the components of the resultant force are

$$-\tfrac{1}{4}GKN^2\,\delta\theta\,.\,\sin 2n, \quad \text{and} \quad -\tfrac{1}{4}GKN^2\,\delta\theta\,.\,\cos 2n,$$
respectively.

If the field is moving with respect to the rotor with velocity $+\omega$ we can write

$$n = -\nu\omega t + n'$$

whence we see that the resultant force vector rotates with velocity $-2\nu\omega$ with respect to the rotor. On the other hand, when $G = 2\nu - 1$ the velocity of the resultant force vector is $+2\nu\omega$ with respect to the rotor.

When $G = (\nu - \mu + 1)$ the resultant sine and cosine components are

$$\tfrac{1}{2}GKMN\,\delta\theta\,.\,\sin(n-m) \text{ and } \tfrac{1}{2}GKMN\,\delta\theta\,.\,\cos(n-m).$$

Writing

$$m = -\mu\omega_1 t + m' \quad \text{and} \quad n = -\nu\omega_2 t + n'$$

where $\omega_1$ and $\omega_2$ are measured with respect to the rotor, we see that the speed of the resultant force vector with respect to the rotor is $(\mu\omega_1 - \nu\omega_2)$.

In the same way we find that

when $G = \nu - \mu - 1$ the speed is $-(\mu\omega_1 - \nu\omega_2)$
when $G = \nu + \mu + 1$ the speed is $+(\mu\omega_1 + \nu\omega_2)$

and when $G = \nu + \mu - 1$ the speed is $-(\mu\omega_1 + \nu\omega_2)$.

In all these cases it will be found that the speed of the force vector in space is $Gn_0 - 2f$, where $n_0$ is the speed of the rotor in revs. per sec., and $f$ is the frequency of supply.

The effect of staggering the rotor slots through one slot-pitch is to make constant the average permeance along any line on the circumference drawn parallel to the axis, and therefore if we consider only the resultant of the radial forces across such a line these resultants will always be in equilibrium, so far as the effects considered under Case (*b*) are concerned, but the radial force is not uniformly distributed along such a line, and if $G$ has one of the values referred to above the forces may be greatest in the middle and least at the ends of one axial line, and least in the middle and greatest at the ends of a diametrically opposite line. Thus there may still be a rotating bending moment acting on the rotor which may conceivably produce appreciable effects on a long rotor.

### (10.)

We must now see what rules can be deduced to enable us to choose numbers of slots for squirrel-cage rotors which will avoid these troubles.

(1) *To avoid the effects of interference between fields with numbers of poles differing by two.*—In a three-phase motor the numbers of poles in the component stator fields are $p$, $5p$, $7p$, $11p$, etc., or, generally $(6d \pm 1)p$, and in a single-phase or two-phase motor they are $p$, $3p$, $5p$, $7p$, $9p$, etc., or, generally, $(4d \pm 1)p$.

Therefore for a three-phase motor, by Equation (2), we must have

$$(6d_1 \pm 1)p \pm 2 \neq 2Gd + (6d_2 \pm 1)p$$

$d_1$ and $d_2$ being positive integers. This reduces to $Gd \neq pd_3 \pm 1$, where $d_3$ is a positive or negative integer, and since $d = -1$ is the only case of practical importance we finally obtain $G \neq pd_3 \pm 1$, i.e. the number of slots in the rotor must not differ by unity from any multiple of the number of poles for which the stator is wound. For single- and two-phase motors we get the same result. In the case of a four-pole machine, for instance, the rotor must not have an odd number of slots.

(2) In Case (*b*) of Section 9 we have seen that we should not have $G = 2\nu \pm 1$, nor $G = \nu \pm \mu \pm 1$.

For three-phase motors, therefore, we must have

$$G \neq p(6d_1 \pm 1) \pm 1$$

and $$G \neq \tfrac{1}{2}p[(6d_1 \pm 1) \pm (6d_2 \pm 1)] \pm 1$$

Both of these conditions are included in the general condition in Case (1) and the same is true for single- and two-phase motors; thus *if the number of rotor slots is chosen so that it does not differ by unity from any multiple of the number of poles, noise arising from all the causes considered in this paper will be avoided.*

The results of an investigation have been published * recently in which a four-pole, 24-slot stator was tested with several rotors having different numbers of slots. Without exception the rotors with odd numbers of slots were noisy, whilst those with even numbers were quiet.

### (11.)

In order to obtain some experimental confirmation of the foregoing theory the following measurements have been carried out by Mr. W. G. Spencer and Mr. E. L. Sainsbury at Woolwich Polytechnic. The machine employed in the experiments was a 4-h.p. six-pole, 50-period, three-phase motor by a well-known British maker. The squirrel-cage rotor had 41 slots, skewed through one slot-pitch, and the stator had a full-pitch winding in 54 slots. During the starting period this machine ran quite silently at low speeds and also at full speed, but when supplied at normal frequency a definite musical note was emitted between speeds of 600 and 750 r.p.m., and it may be assumed that the speed of the rotating side-pull coincides with the critical speed of the rotor at about the middle of this range. The machine was very rigidly constructed and consequently the note was so faint as to be negligible from a commercial point of view, though it was clear enough for experimental purposes.

For this machine, since $p = 6$, we have $G = 41 = 7p - 1$, a number which should be avoided, according to Section 9.

If we consider the action of the 7th multiple field on this rotor we have $p_3 = 42$, and the possible values of $p_4$ are

$$p_4 = (2 \times 41 \times d) + 42$$

substituting successively 0, $-1$, $+1$, $-2$, $+2$, etc., for $d$, we obtain the following series of values for $p_4$ .. 42, $-40$, $+124$, $-122$, etc. The 42-pole field produced by the rotor currents combines with the original $7p$-pole field (reducing its value), and this resultant, together with the field for which $p_4 = -40$, produces a rotating side-pull which is the cause of the note observed. The two fields of 122 and 124 poles also produce a rotating side-pull.

Taking $f$ as the frequency of supply and $n_0$ as the speed of the rotor we have

$$p_3 = p_2 = 42\,; \quad p_4 = p_1 = 40$$

$$n_3 = \frac{2 \times f}{6} \times \frac{1}{7} = \frac{2f}{42}$$

i.e. one-seventh of the speed of the main field, and, since $d = -1$,

$$n_4 = \frac{-82n_0 + n_3 \times 42}{-40} \quad \text{[by Eqn. (9)]}$$

$$= \frac{-82n_0 + 2f}{-40}$$

$$= n_1$$

Since $n_2 = n_3$, the speed of the force vector [by Eqn. (5)] is

$$\tfrac{1}{2}(42n_3 - 40n_4) = 2f - 41n_0$$

We are not concerned with the direction of this rotation,

---

[*] W. Stiel: *Zeitschrift des Vereines deutscher Ingenieure*, 1921, vol. 65, p. 147.

and in order to deal with a positive quantity we may write for the frequency of the note emitted

$$41n_0 - 2f$$

For the other two fields, with 122 and 124 poles respectively, the speeds must be calculated as for $n_4$ above.

The speed of the 122-pole field is ($d$ being $-$ 2)

$$\frac{-164n_0 + 2f}{-122} = n_1$$

while that of the 124-pole field is ($d$ being $+$ 1)

$$\frac{82n_0 + 2f}{124} = n_2$$

The speed of the force vector in this case is

$$\tfrac{1}{2}(124n_2 - 122n_1)$$
$$= -41n_0 + 2f, \text{ as before}$$

The pitch of the loudest note emitted by the machine was rather lower than 384 per sec., but for convenience this pitch was taken as standard during the experiments, and a tuning-fork was used as a standard of reference. Power was supplied to the motor at several different frequencies between 0 and 60 periods per sec., and at each frequency the speed was observed at which the note emitted coincided with that of the tuning-fork. The points marked in Fig. 11 show the actual readings obtained, and the line drawn amongst them represents $41n_0 - 2f$. It will be seen that substantial agreement has been obtained. There are two points on the extreme left of the figure for which it does not seem possible to account on the basis of the theory here given.

The faintness of the note emitted by this machine is due to the fact that the slots were skewed, and the effect would have been eliminated entirely if the obliquity had been such that the slot openings extended across two slot-pitches instead of one, though this is scarcely practicable and, in the present case, is quite unnecessary.

Considerable difficulties had to be overcome in order to obtain the results shown in Fig. 11, and the author wishes to express his indebtedness to Messrs. Spencer and Sainsbury for the care and trouble which they took in making the experiments. It was hoped to show that the critical speed of the rotor was in the neighbourhood of 384 revs. per sec. In this, however, we have not yet been successful, and further experiments are in progress.

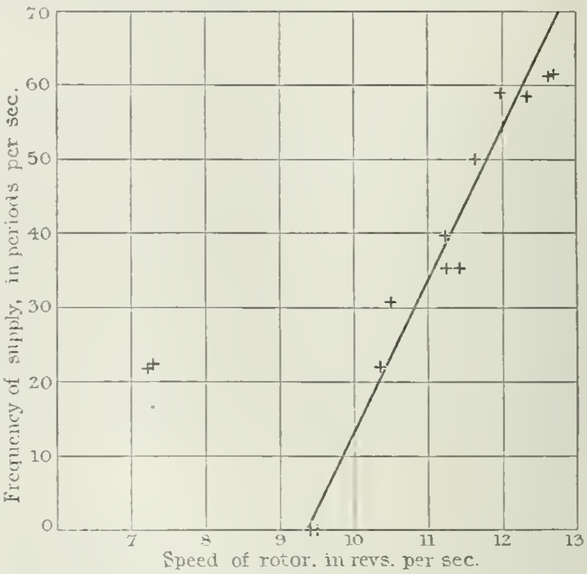


Fig. 11.

# AN ELECTRICAL TIMING DEVICE FOR SHORT INTERVALS.*

By Professor DAVID ROBERTSON, D.Sc., Member, and NORMAN F. FROME, B.Sc., Student.

(*Paper received 21st April, 1922.*)

## SUMMARY.

The paper describes a timing device consisting of an inductive resistance in a Wheatstone bridge. The theory of the device is given and an example of its application.

## GENERAL DESCRIPTION.

This arrangement was devised with a view to its application to an industrial purpose, but doubts as to the suitability of delicate relays under works conditions soon caused it to be abandoned for that particular object. As, however, there are uses for it in the laboratory, and it can be easily made up from apparatus which is usually in stock in an electrical laboratory, it is thought that a description may be of interest.

A Wheatstone bridge is made up with three non-inductive arms and one highly inductive arm, as in Fig. 1. When the slider is at C, the point of balance for steady conditions, there will be, on switching on the current, a momentary deflection indicating that the slider should be moved to the left. Now place the slider at H, to the left of C. Immediately after switching on, and before the current in the inductive branch has reached an appreciable value, the inductance will absorb practically the whole voltage. Thus D and A will be very nearly at the same potential and the galvanometer current will flow from D to H. Later on, however, the current will flow from H to D. Thus, the galvanometer current will reverse at a particular instant in the growth of the current in the upper arms, and this instant can be varied by adjusting the position of H.

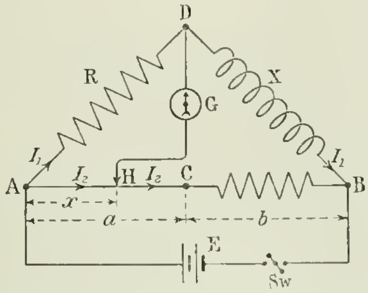


FIG. 1.—Connections of inductive timing device.

If, instead of the galvanometer, a polarized relay be employed, the first current will deflect the tongue against one stop and the second current against the other. By suitable connections, these movements can be made to close or open an electrical circuit for a definite interval of time, and this secondary circuit may be utilized to control any required operation. By adding other relays, connected to different positions of H, several operations can be obtained in a definite timed sequence.

In the experiments referred to below, R was a 1-ohm coil, AC a 1-ohm slide-wire, while R and X had resistances of 6·44 ohms. X had an inductance of about 1·55 henrys (it is not quite independent of the current used) and thus the time-constant of the R–X circuit was 0·209 second.

The core of the reactor, X, is a rectangle 4 in. × 5 in., with a window 2 in. × 3 in., made from ⊓-shaped Stalloy stampings about 15 mils thick. There are 140 sheets in each packet, giving a gross depth of 2·25 in. and a net depth of about 2·0 in. A press-spahn sheet 11 mils thick was inserted between the two packets at each joint so as to give a definite gap. The effective length of the gap is considerably greater, owing to the unevenness of the edges of the sheets, and to the presence of varnish. The measured inductance corresponds to an effective gap length of 19 mils at each side.

The magnetic path in the iron is 13 in., or say 350 times the effective length of the two gaps. This is somewhat on the high side, but the magnetism left on switching off is still under 5 per cent of the maximum.

The packets of stampings are inserted into two coils joined in series. Each coil has 480 turns in 10 layers, the wire being 20 S.W.G. copper having a diameter of 36 mils bare, and 50 mils over the cotton insulation.

Each gap in the magnetic circuit comes at the centre of a coil. With this arrangement there is little magnetic leakage and the inductance can be calculated with an accuracy practically equal to that with which the gap can be measured.

Current was obtained from a 4-volt storage battery. The current in the reactor would thus be just over ½ ampere, giving a flux density in the iron of about 7 000 C.G.S. units.

Standard Post Office polarized relays were used for the tests, the two 100-ohm coils being in parallel, giving a resistance of 50 ohms. They operated with a minimum current of 2·5 to 5 milliamperes, or 125 to 250 millivolts, according to the adjustment. At first they gave some trouble owing to the vibration of the table when the main switch was put on, but this was eliminated by supporting the relays on felt pads, or on a separate table.

## THEORY.

At the initial instant, $E_L$, the electromotive force induced in $X$, is equal to $E$, the battery E.M.F., but it decays according to the law

$$E_L = E \times \epsilon^{-T/T_0}, \text{ where } T_0 = L/(R + X)$$

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

For simplicity, we shall assume that the battery resistance and the galvanometer current are negligible, and that we need not take account of the effect of the inductance of the galvanometer branch.

Then, at the instant of the reversal of the galvanometer current, H and D are at the same potential. Consequently,

$$RI_1 = xI_2 \quad \text{or} \quad I_1 = I_2 \times x/R$$

$$\begin{aligned} \text{and} \quad XI_1 + E_L &= (a + b - x)I_2 \\ \therefore \quad E_L &= (a + b - x)I_2 - (xX/R)I_2 \\ &= (a + b - x - xX/R)I_2 \\ &= (a + b - x - xb/a)E/(a + b) \\ \therefore \quad E_L/E &= \left\{a(a + b) - x(a + b)\right\} \div a(a + b) \\ &= (a - x)/a \end{aligned}$$

$$\text{Hence,} \quad \epsilon^{-T/T_0} = (a - x)/a$$

$$\begin{aligned} \text{or,} \quad (T/T_0) \log \epsilon &= \log a/(a - x) \\ \therefore \quad T &= T_0 \times \log a/(a - x) \div \log \epsilon \end{aligned}$$

This gives the following values for the ratio $T/T_0$:—

| $x/a$ .. | .. 0 | 0·1 | 0·2 | 0·3 | 0·4 | 0·5 | 0·6 | 0·7 | 0·8 | 0·9 | 0·95 | 1·0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T/T_0$ | .. 0 | 0·105 | 0·223 | 0·357 | 0·511 | 0·694 | 0·917 | 1·205 | 1·610 | 2·303 | 3·000 | ∞ |

### CALIBRATION.

Owing to the various disturbing causes mentioned below, the scale cannot be calculated from the constants of the apparatus; it must be calibrated. For this purpose, the duration of the contact in the operated position of the relay was measured by the method of charging a condenser through a high resistance, using the relay as a charge-and-discharge switch with the bias in the discharge position, and the first current sending it to the charge position. A knowledge of the resistance in the charging circuit, and of the capacity of the condenser, enables the duration of the contact to be calculated from the ratio of the ballistic deflection to that obtained on discharging the condenser after it has been completely charged. For

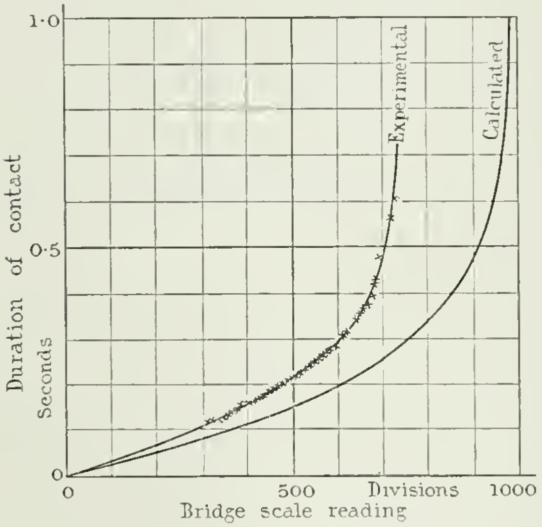


FIG. 2.—Calibration curve of inductive timing device.

$$Q = Q_0(1 - \epsilon^{-T/T_0}),$$

where $T_0$ is now equal to $CR$. Hence,

$$T = T_0 \log Q_0/(Q_0 - Q) \div \log \epsilon$$

In the experiments, $R$ was 200 000 ohms and $C$ 1 microfarad, so that $T_0$ was 0·2 second.

As will be seen from the graph in Fig. 2, the duration of the contact differs very considerably from the value calculated from the constants of the reactor. There are several causes for this besides the mechanical inertia of the tongue of the relay. Its low voltage-sensibility leads to a considerable delay in its operation, which is enhanced by the effects of the inductance of the relay coils and by the eddy currents in the relay core. Moreover, with the high ratio of iron length to gap length in the core of the reactor, combined with the comparatively high flux density to which it was necessary to run it in order to get reasonable sensibility in the relays, the inductance varied nearly 5 per cent between the maximum value and that with the steady current, while the initial value was about 10 times smaller. Consequently the growth of the current would depart appreciably from the simple exponential law obtained by assuming constant inductance.

Considerable care is required to adjust the relay to the most sensitive setting, and the reading obtained for any given position of the slider varies greatly with this adjustment. On the other hand, with one setting of the relay, the readings can be repeated over and over again with good accuracy so long as the slider is not too near either end of the scale, where the voltage available for operating the relay is too small for certain action. Also, it has been found possible after altering the relay to bring it back again to the former setting by adjusting it to give the same deflection at some one point of the scale; the calibration curve will then be the same as before.

### EXAMPLE OF THE USE OF THE DEVICE.

The apparatus was employed for calibrating the scale of an electrical chronometer which was made in the laboratory a number of years ago.* This chronometer was adapted from a Westinghouse type " O " ampere-hour meter by removing the shunt and inserting a series resistance adjusted so that the rotor makes approximately one revolution per second when run on a 4-volt battery. A scale of 100 divisions was marked round the rotor disc to give hundredths of a second, and a scale of seconds on a toothed wheel gearing with the pinion on the rotor spindle.

The instrument has a disc armature with an open-coil winding and a three-part commutator, the windings being enclosed in a double disc of aluminium which also

* D. ROBERTSON: *Journal I.E.E.*, 1915, vol. 53, p. 314.

acts as a brake. Two permanent magnets serve both as motor magnets and as brake magnets.

It was suspected that owing to the action of the commutator there might be sufficient variation of torque in one revolution to make the reading obtained with a short interval of time depend on the initial position of the rotor.

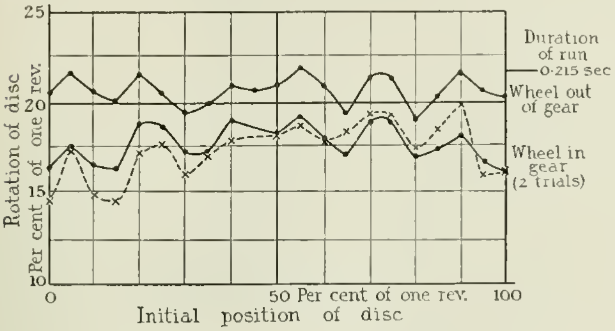


Fig. 3.—Calibration of scale of an electrical chronometer.

The inductive device was therefore connected to start and stop the chronometer, the disc of the latter being previously set to some particular position which was varied from time to time. Fig. 3 gives the results and shows unmistakably that the suspected effect does exist, although not to a serious extent. The six peaks on the upper graph, taken with the wheel out of gear, correspond to the six positions in one revolution in which the relative positions of brushes and segments are the same, three occurring at each brush.

The lower graphs, representing two tests with the wheel in gear, show in addition a variation of friction caused by eccentricity of the pinion. Differences between one of these curves and another may similarly be caused by eccentricity or irregularity in the gear wheel, and discrepancies in the same graph may also be due to the same cause if care is not taken to have the same teeth of the wheel in mesh at the separate trials for each point on the curve.

In conclusion, the authors desire to express their thanks to the governors of the Merchant Venturers' Technical College for the facilities for carrying out this work.

# THE ENGINEER AND MANUFACTURING COSTS.

By F. C. Lawrence, M.C., B.Sc.Tech., Student.

(Abstract *of paper read before the* North-Western Students' Centre, 6*th December*, 1921.)

### Summary.

The phases of costing discussed in the paper are those which will be of most interest and use to engineers in shops and offices.

An example of the methods of calculating job costs is given, the proportions of the components of the factory costs of various engineering products are illustrated, and the use of mechanical appliances in various calculations is shown to give accuracy and save time in arriving at costs.

The functions of a "work-in-progress" account are described in terms, translated from accountancy to their shop equivalents, showing the actual connection between such an account and the production of a department.

The effect of inaccuracy, which may so easily occur in shop records, is traced through costs to show the delay and unreliability caused thereby; and the necessity of avoiding this inaccuracy is emphasized.

The analysis of the costs of completed jobs gives information which is useful to those engaged in all branches of the industry, and a detailed example of such an analysis is given and described.

As an example of the very many practical services given by a cost department, the relation between the rate of production and the proportion of factory overhead expenses in factory cost is cited.

### Introduction.

In presenting this paper it has been the author's aim to show those aspects of the subject which will enable the engineer to appreciate, first the dependence of costing on his efforts to ensure correct data being sent from the shops and offices to the cost department, and secondly, the value of the facts and figures which, based upon that data, the cost department is able to give to him and to the other members of the factory administrative and executive staffs.

In this abstract it has been thought advisable to delete the introduction to the elements of costing which was embodied in the original paper, and to retain as fully as possible the explanations of the source of the figures as finally presented by the cost department, and their value to those concerned.

Whilst a knowledge of the first principles of costing is, therefore, assumed, it has been found necessary to include a figure showing of what the factory cost is composed and determining the terminology used throughout the paper.

One of the most important factors in satisfactory costing lies in the collection and distribution of the factory overhead expenses to departments and to jobs, a subject which should be of especial interest to engineers.

Only the general method (which is considered by most engineering firms to be best) of distributing the expenses to jobs in the shops, i.e. the machine-hour rate, is indicated in the paper. By the use of this method, for every hour worked on a machine in the shop there is added to the cost of the job an amount equal to the rating of that machine, and by this means the whole of the factory overhead expense should be absorbed by the production of the shops.

Hand labour is classified as a machine group, with its own distinctive rate.

### The Grouping of Machine Tools.

To arrive at machine-hour rates for the distribution of factory overhead expenses, an analysis is made of each item of these expenses so as to divide it amongst the groups of machine tools in a department. From this are determined the total factory overhead expenses attributable to each group. From the records of the machine tools, the working space occupied, the power consumption, the original value and depreciation, the consumption of tools, and any particular expense items, the group into which each one will fall can be determined.

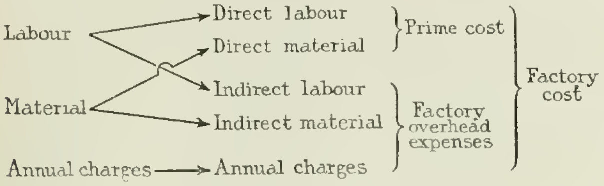
The group number is composed of two figures and is the number noted by the worker on his job ticket. The tens indicate the machine-hour rate and the units the type of machine tool. A practical example is give in Table 1, from which it is seen that Group 24 may contain a number of 5 ft. radial drills rated at 2s. 6d. per hour, while Group 78 covers 10 ft. planers at 9s. per hour.

Certain machine tools are not engaged on direct machine labour, and the cost of running and maintaining them is charged to factory overhead expenses, so that they do not themselves carry a machine-hour rate.

### An Example of Factory Cost.

The manufacture of a large induction motor has been selected as an example and it is proposed to show details in the procedure of arriving at its cost in the section of the cost department, dealing with the costs of the motor assembly department of the factory.

The motor is manufactured on order No. 7106, and during the period of manufacture in the shops, job tickets, in large numbers, will be made out for work done on this order, and each will bear this number. Some will come from the foundry, the forge, the punching department, the coil-winding department and other feeder departments, but such tickets will be dealt with by the feeder department cost sections, for they will receive them with the material requisitions from the motor assembly departments. They will cost the various materials ordered from their departments and deliver to the motor cost section the requisitions on which the complete cost of their supplies will be given, showing in each case the labour, material and factory overhead expenses, and the total (i.e. factory cost), so that for any transfer in the shop from one department to another of finished or part-finished goods, there will be a corresponding transfer in the cost department of a requisition showing the cost.



The synthesis of factory cost.

If in making out the specification of material on any job for the shops, the specification clerk has an extra copy of the specification made which he forwards to the cost clerk concerned, then the latter will at once have before him, in costing the job, the full particulars as to the size, quality, quantity and raw material of each item of the finished machinery or apparatus.

Now, each item is designated on the specification by its drawing number, item number, pattern number and style number, or by whichever of these is desirable. The worker in the shops marks these numbers clearly in the spaces provided on his job ticket, so that it will be seen to be not a very difficult process to connect precisely the job ticket representing any labour in the shops with the materials specified, so that if the original specification sheets are provided with columns for labour, material and factory overhead expenses for the use of the cost department, the cost clerk can collect on these sheets the cost of each specified item, knowing, if he has a requisition or job ticket which does not agree with any item in the specification, either that it has been wrongly entered in the shops or that the specification has been altered, which causes he can at once investigate. If he has shop records showing more than the specified quantities in any item, some previous part has been scrapped or returned for alteration (which scrapping or alteration should have been notified to him by the shops on a suitable form) and again he can trace the omission to its source and discover the true facts.

The cost clerk will receive weekly from the timekeeping department the whole of the week's job tickets for his section, after they have been used to complete the employee's wages. He will receive from the stores the whole of the requisitions, with the costs entered on them from their records, and he will receive from other costing sections the inter-departmental requisitions. His first duty is to sort these under their job number, and he will select the whole of the records booked to this number. From the job tickets he will make a list of the hours worked and the money paid to workers in each machine-hour group, as shown on the left-hand side of Table 2.

The amounts shown on the requisitions will be posted on to the specification against the corresponding items, and the totals of labour, material and overhead expenses will be posted on to the summary sheet of Job No. 7106 against the date.

Each week this procedure will be adopted, from the date when the specifications are received by the cost clerk to a convenient date after he has received the warehouse receipt, which tells him that the motor is

TABLE 1.

*Grouping of Machine Tools.*

| Sub group numbers | Types of machine tools | Factory overhead machine group numbers | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
| 1 | Centring | Hand labour, and hydraulic presses and bending machines (hand) | — | — | — | — | — | — |
| 2 | Vertical boring mills | | — | 60 in. to 80 in. | Nos. 10 and 8 | 10 ft. to 12 ft. | 16 ft. | — |
| 3 | Horizontal boring mills | | | 3¾ in. dia. bar | — | — | — | — |
| 4 | Drilling | | 20 in. vertical<br>5 ft. radial<br>3 ft. spindle | 17 ft. to 19 ft. radial | | | | |
| 5 | Surface grinders | | | | — | — | — | — |
| 6 | Lathes | | 20 in. to 42 in. engine | 63 in. engine | — | 72 in. engine | — | |
| 7 | Milling | | — | 24 in. horizontal slabs | 42 in. slab | — | — | — |
| 8 | Planing | | 2 ft. to 3 ft. | 4 ft. to 5 ft. | 6 ft. | — | 7 ft. | 10 ft. |
| 9 | Miscellaneous | | 15 in. slotting and shaping, No. 5 keyway cutter | Portable 60 in planer | — | — | — | — |
| | Machine-hour rate | 1s. 6d. | 2s. 6d. | 3s. | 4s. | 5s. | 7s. 6d. | 9s. |

completed and ready for shipment. The convenient date is a few days after the reception of this receipt, thus leaving time for the last few job tickets and requisitions to reach him. He can then arrive at the total figures of labour, material and overhead expenses and the total factory cost of the motor.

TABLE 2.

*Abstract of Labour and Factory Overhead Expenses.*

*Abstract of the Labour and Overhead Costs on Job No.* 7106. *Week ending* 10/1/23.

| | Labour | | Factory overhead | |
|---|---|---|---|---|
| Group No. | Hours | Wages cost | Rate | Cost |
| | | £ s. d. | s. d. | £ s. d. |
| 10 | 52½ | 5 0 7 | 1 6 | 3 18 9 |
| 20 | 4 | 0 9 2 | 2 6 | 0 10 0 |
| 30 | 5 | 0 14 1 | 3 0 | 0 15 0 |
| 40 | — | — | 4 0 | — |
| 50 | 3 | 0 7 5 | 5 0 | 0 15 0 |
| 60 | 8 | 1 0 6 | 7 6 | 3 0 0 |
| 70 | — | — | 9 0 | — |
| Totals . . | 72½ | 7 11 9 | — | 8 18 9 |

### FOUNDRY COSTS.

The description given of costing methods to be used in engineering works has been made as simple as possible. In actual practice the cost accountant is continually meeting problems of no small magnitude.

The costing of the products of a foundry requires very careful handling. Arbitrary values are too often used in distributing the costs, thus leading to wrong results. An iron foundry is naturally divided into at least four parts—the melting, moulding, core-making and dressing sections—each of which calls for different costing methods. The metal at the cupola spout may best be costed at so much per pound, whilst the labour in the other sections may, in some cases, be booked to jobs, and in others to processes. The factory overhead expenses need different treatment in the various sections. The costs of individual castings may all be determined at the end of a month, or predetermined costs may be used throughout the month and an adjustment made at the end of the month. In addition to making castings for the assembly departments, the foundry casts its own equipment. All these and other points need attention, and it is only by a thorough appreciation of them that the true foundry costs can be found.

### PERCENTAGE COMPOSITION OF FACTORY COSTS.

In order that the relative importance of the component parts of factory costs may be appreciated, Table 3 has been prepared to show, for a few departments in a typical electrical engineering firm, the percentage composition of its costs.

The question of the standardization of costing methods is here involved. Some firms may include certain material and labour costs as factory overhead expenses, while others may regard them as direct material and direct labour costs; for the border line between prime costs and overhead expenses is not sufficiently distinct to form a universal division.

The figures in the table given must therefore be regarded merely as indicative of the proportions. It will be seen that the assembly departments have, in general, a larger percentage of direct labour and overhead expenses than the feeder departments, because the figures given for them include the labour and overhead expenses transferred from the feeder departments in part-finished goods.

TABLE 3.

*Percentage Composition of Overall Departmental Factory Costs.*

| Departments | Direct labour | Factory overhead | Material | Labour in factory overhead, i.e. indirect labour | Total labour |
|---|---|---|---|---|---|
| *Assembly.* | per cent | per cent | per cent | per cent | per cent |
| A—Manufacturing rotary converters, alternators and motors . . . . . . . . . . . . | 26 | 27 | 47 | 20 | 46 |
| B—Manufacturing large electrical transformers . . | 19 | 22 | 59 | 12 | 31 |
| *Feeder.* | | | | | |
| C—Winding and insulating coils . . . . . . | 18 | 12 | 70 | 10 | 28 |
| D—Manufacturing sheet punchings . . . . . . | 13 | 21 | 66 | 12 | 25 |
| E—Forge . . . . . . . . . . . . . . | 16 | 27 | 57 | 11 | 27 |
| F—Foundry . . . . . . . . . . . . | 35 | 31 | 34 | 22 | 57 |

The varying ratio of overhead to direct labour expenses is marked; for the forge it is nearly 170 per cent, while for the coil-manufacturing department it is only 66⅔ per cent.

The annual charges are, on an average, about 10 per cent of the factory overhead expenses.

Such figures as the above prove to be very useful in many statistical surveys.

### The Use of Calculating Machines.

The processes of costing entail a great amount of sorting of documents and compilation of figures which, if performed by hand, would become not only tedious to the clerks involved but expensive to the firm. For this reason many machines have been called to the service of cost systems, and by their means the speed and accuracy with which cost returns are presented have been greatly increased, while the work of a cost clerk has lost much of its tedium.

The Burroughs adding machine is one of the smaller types arranged for adding sums of money. The Comptometer, another portable machine, does not make a record of the amounts but shows the increasing sum on a series of counters of cyclometer type.

Table 4.

*Statement of Work in Progress.*

*(A) Assembly Department. Comparative Statement of Work in Progress,* 1923.

| *Charges.* | October<br>£ | November<br>£ | December<br>£ |
|---|---|---|---|
| (1) Work in progress at beginning of month (brought forward) .. .. | 31 629 | 28 165 | 26 622 |
| (2) Direct wages (from the shop pay-roll) .. .. .. .. .. | 872 | 913 | 1 097 |
| (3) Factory overhead absorbed .. .. .. .. .. .. .. | 1 009 | 1 187 | 1 310 |
| (4) Goods received from other departments .. .. .. .. .. | 2 516 | 2 136 | 3 373 |
| (5) Direct raw and finished materials .. .. .. .. .. .. | 1 275 | 1 521 | 2 151 |
| (6) Engineering and draughting salaries, etc. .. .. .. .. .. | 35 | 71 | 142 |
| (7) *Total charges* .. .. .. .. .. .. .. .. .. | £37 336 | 33 993 | 34 695 |
| *Credits.* | | | |
| (8) Deliveries to warehouse and other departments .. .. .. .. .. | 7 702 | 6 733 | 7 028 |
| (9) Goods for own uses .. .. .. .. .. .. .. .. | 547 | 211 | 101 |
| (10) Goods shipped direct from outside suppliers .. .. .. .. | 922 | 427 | 347 |
| (11) *Total credits* .. .. .. .. .. .. .. .. .. | £9 171 | 7 371 | 7 476 |
| (12) Work in progress at end of month carried to next month .. .. | 28 165 | 26 622 | 27 219 |
| (13) Average monthly output for last six months .. .. .. .. | 7 219 | 6 814 | 6 371 |
| (14) Equivalent turnover ratio (i.e. no. of months' output in work in progress) | 3·9 | 3·9 | 4·3 |

A modified form of the Burroughs machine with duplicate keyboards gives a whole statement of figures at once, while its operation is speeded up by means of an electrical motor drive. This machine is adaptable to the whole preparation of pay-rolls and to other uses in the cost department, while practically the whole of the financial accounts can be prepared on it.

In the processes of summarizing and analysing costs these machines and others of similar function are invaluable as time savers, and in ensuring accuracy of compilation.

At the other end of the scale we have such elaborate machines as the Powers and Hollerith tabulating machines, the latter of which has been very fully described in an article by Mr. E. W. Workman.* These machines should interest the engineer, and particularly the electrical engineer, because of their construction and operation. Their use is restricted to the larger firms, as the expenses of rent (they cannot be purchased) and of maintenance make it necessary that they should be in constant use in order to be economical.

To arrive only at the total cost of orders, the totals of labour and materials costs are needed. To analyse costs, as will be seen later, much detail is required which should not prematurely be called for.

### Work in Progress.

A most important function of the cost department and one which is of great help to engineers in the shops, is the provision of statements at stated intervals of the work in progress in the shops.

While work is being fashioned in the shops into the products of the factory, it represents portions of the invested capital of the firm. It is obvious that money is made by the turning over of capital, which in turn is effected by the constant progression of work through the shops. It is the duty of the production engineer to arrange the programme of the orders being filled in the shops, and it lies with the cost department to inform him of the value of the work he is thus arranging.

The work in progress is daily absorbing or being charged with new material, labour and factory overhead expenses, and likewise it is being relieved of and receiving credit for the goods it turns out to other departments and the warehouse or shipping department.

Having taken a physical inventory of the value of the total work in progress in a department at the end of a year, the cost department can, each succeeding month, charge the department with its absorption of material, labour and factory overhead expenses, and credit it with its output of finished goods, from the cost records which it possesses; to arrive at the end of each month at a figure showing the new value of work in progress at that date.

---

* E. W. Workman: "Cost Accounting by Machinery," *Engineering and Industrial Management*, 1921, vol. 6, p. 314.

In addition, it can show exactly how the amount of work in progress is distributed over the various orders being filled in the shops, and indicate the rate at which the invested capital is being turned over.

Table 4 gives a typical departmental work-in-progress comparative statement showing each item of the totals* and the monthly variations. Several small items which occur in actual practice have been omitted for the sake of simplicity.

It will be seen that at the end of September there is work in progress to the value of £31 629, and that it has decreased at the end of October to £28 165, i.e. by 11 per cent. A further decrease of 6 per cent is noticed in November, while December shows an increase of just over 2 per cent.

The efforts of the production engineers in reducing the work in progress, i.e. the working capital locked up in the shops, is reflected in this statement. They were successful in October and November but in December, although the deliveries to the warehouse have increased by over 4 per cent, the arrivals of feeder department materials and raw materials to provide for their programme have overbalanced the increase of deliveries and caused the increase in the work in progress.

The turnover is reflected in item 14, which is the quotient of items 12 and 13. While this may not represent the turnover to a great degree of accuracy, it is a very good guide to the speed at which a department is making money for the firm, the speed being inversely proportional to the turnover.

The incorporation of the cost records as cost accounts in the financial books of the firm enables the gross profit made by each department each month to be ascertained.

Reviewing the items shown in Table 4, it can be seen that item 1 is the resultant figure transferred from the previous month. Item 2 is the total paid to the direct-labour workers in the department, taken from the shop pay-roll. Item 3 is the amount of the factory overhead expenses absorbed by this direct labour. Item 4 consists of the cost of part-finished goods (such as rough castings and forgings) received from the feeder and from other assembly departments. The raw materials received and the finished parts purchased from outside suppliers and applied to specific orders appear in item 5, in which also is included those finished parts from outside suppliers which are forwarded direct by them to the customers of the firm and which do not go through the shops (such as oil for bearings or for electrical transformers and steam engines for driving alternators, in cases where they are not made by the firm). Item 6 consists of special charges which are not charged to factory overhead expenses, but are specific to certain orders or jobs.

The total cost of all the apparatus delivered to the warehouse and to other departments is included in item 8, while item 9 contains the cost of all apparatus made for "A" department's own use, and of labour on repairs and renewals in the shop. It is obvious that the difference between items 7 and 11, i.e. the total of the credits, represents the value of the work in progress at the end of the month, as shown in item 12.

Since the whole of the direct wages, factory overhead expenses and materials have been used on specific orders, the total of the costs added to these orders during the month will agree with the totals of items 2, 3, 4 and 5. The work for the department itself is done on an internal order and costed in precisely the same manner as customer's orders, and the totals of the costs to date of all orders that have not been closed will agree with the work-in-progress balance, so that should the production engineer query the magnitude of this balance, he can be told at once exactly of what it consists.

## THE SHOP STAFF IN RELATION TO SHOP RECORDS.

If the cost records are to be accurate and reliable, the shop records, which form practically the whole data from which they are built, must be accurate and complete in every detail. In other words, in order that the cost department may give the engineers and the management reliable costs and cost figures, the engineers in the shops must first give to the cost department documents which unerringly represent what actually has taken place in the shops.

Now it is almost impossible for an employee to draw from the stores the direct material which he requires for his jobs without giving requisitions agreeing in detail with the material he receives, as specified for each job.

The direct labour is in most cases accurately accounted for, but even in this case loopholes occur for wrong booking (for example, where the employee spends a short time on each of many small jobs he is liable to book his time spent on several jobs to one only, in order to save himself the trouble of writing out several tickets).

The indirect labour and indirect material bookings are the source of many troubles, and the factory overhead expenses of which they form by far the largest proportion is no small part of the total factory cost, as will have been noted from Table 3. In the first place a foreman will strive to cut down his factory overhead expenses; secondly, the employee will have constantly to refer to a list of overhead items in order to book correctly; and thirdly, unless detailed explanation is given as to what is to be and what is not to be booked to each item of overhead expenses, indecision will lead to a proportion of wrong bookings.

While the cost department will lend its aid in planning the means of booking all the items, the department looks to the engineer in the shops to see that these bookings are correctly made.

If many incorrect bookings are made in the shops it must necessarily take much time on the part of the cost department to have the corrections made, thereby occasioning delay in the presenting of costs, undermining the exactitude of the results, and greatly increasing the expense of running the cost department, with a resultant increase in the cost of each piece of apparatus turned out from the shops.

Dislocation of work, consequent delay and increased expense may also be occasioned by the late receipt of job tickets and requisitions from the shops and stores. In this direction the engineers concerned may help, at

---

* None of the figures used in this paper relate to any particular firm.

TABLE 5.

*Analysis of Factory Cost, Motor Assembly Department.*

Factory Cost of One Induction Motor, Type SR, Frame 4331, 575 H.P., Three-phase, 50 Periods, 500 Volts, 480 R.P.M., for A.B. Company, Limited. Order No. 7106.

| Column | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parts | Section No. | Quantity | Name of part | Weight | Mach. group no. | Direct hours | | Labour cost | | Overhead cost | | Material costs | Total factory costs |
| | | | | | | Groups | Parts | Groups | Parts | Groups | Parts | | |
| | | | | lb. | | | | £ s. | £ s. | £ s. | £ s. | £ s. | £ s. d. |
| Mech'l parts of stator | 1 | 1 | Cast-iron yoke .. | 2 800 | 10 | 60 | — | 4 10 | — | 4 10 | — | — | — |
| | | | | | 30 | 25 | — | 2 5 | — | 3 15 | — | — | — |
| | | | | | 50 | 35 | — | 3 10 | — | 8 15 | — | — | — |
| | | | | | 70 | 5 | — | 0 10 | — | 2 5 | — | — | — |
| | | | | | All | — | 125 | — | 10 15 | — | 19 5 | 96 10 | 126 10 0 |
| | 2 | — | Magnetic circuits .. | 2 000 | — | — | — | — | — | — | — | 201 2 | 201 2 0 |
| | 3 | — | Assembling circuits .. | — | 10 | 125 | 125 | — | 10 14 | — | 9 7½ | 4 1 | 24 2 6 |
| | 4 | 2 | W.I. end plates .. | — | 30 | 15 | 15 | — | 0 15 | — | 2 5 | 16 15 | 19 15 0 |
| | 5 | 2 | End brackets .. .. | 2 400 | 10 | 180 | — | 16 1 | — | 13 10 | — | — | — |
| | | | | | 20 | 20 | — | 1 14 | — | 2 10 | — | — | — |
| | | | | | 30 | 45 | — | 4 11 | — | 6 15 | — | — | — |
| | | | | | 50 | 35 | — | 3 12 | — | 8 15 | — | — | — |
| | | | | | 60 | 30 | — | 4 3 | — | 11 5 | — | — | — |
| | | | | | All | — | 310 | — | 30 1 | — | 42 15 | 137 16 | 210 12 0 |
| Mech'l parts of rotor | 6 | 1 | Cast-iron spider .. | 1 600 | 10 | 10 | — | 0 13 | — | 0 15 | — | — | — |
| | | | | | 20 | 35 | — | 3 7 | — | 4 7½ | — | — | — |
| | | | | | All | — | 45 | — | 4 0 | — | 5 2½ | 81 2 | 90 4 6 |
| | 7 | — | Magnetic circuits .. | 1 700 | — | — | — | — | — | — | — | 168 7 | 168 7 0 |
| | 8 | — | Assembling circuits .. | — | 10 | 135 | 135 | — | 13 6 | — | 10 2½ | 2 1 | 25 9 6 |
| | 9 | 2 | End plates .. .. | 350 | 30 | 20 | 20 | — | 2 1 | — | 3 0 | 33 3 | 38 4 0 |
| | 10 | 1 | Shaft .. .. .. | 800 | 20 | 55 | — | 5 7 | — | 6 17½ | — | — | — |
| | | | | | 30 | 5 | — | 0 12 | — | 0 15 | — | — | — |
| | | | | | All | — | 60 | — | 5 19 | — | 7 12½ | 53 1 | 66 12 6 |
| Elec'l parts of stator | 11 | — | Coils and connections | 700 | — | — | — | — | — | — | — | 297 10 | 297 10 0 |
| | 12 | — | Winding and assembling | — | 10 | 475 | 475 | — | 21 2 | — | 35 12½ | — | 56 14 6 |
| | 13 | — | Brush-gear .. .. | — | 10 | 10 | 10 | — | 1 1 | — | 0 15 | 37 16 | 39 12 0 |
| | 14 | — | Terminals, etc... .. | — | 10 | 25 | 25 | — | 1 17 | — | 1 17½ | 19 8 | 23 2 6 |
| | 15 | — | Trifurcating box .. | — | — | — | — | — | — | — | — | 17 1 | 17 1 0 |
| Elec'l parts of rotor | 16 | — | Coils and connections | 600 | — | — | — | — | — | — | — | 416 1 | 416 1 0 |
| | 17 | — | Winding and assembling | — | 10 | 425 | 425 | — | 23 7 | — | 31 17½ | 65 5 | 120 9 6 |
| | 18 | — | Slip-rings, etc. .. .. | — | 10 | 5 | 5 | — | 0 11 | — | 0 7½ | 16 18 | 17 16 6 |
| | 19 | 2 | Pillow blocks .. .. | 750 | 10 | 85 | — | 7 7 | — | 6 7½ | — | — | — |
| | | | | | 20 | 45 | — | 3 11 | — | 5 12½ | — | — | — |
| | | | | | 30 | 60 | — | 5 19 | — | 9 0 | — | — | — |
| | | | | | All | — | 190 | — | 16 17 | — | 21 0 | 27 2 | 64 19 0 |
| Other parts | 20 | 2 | Bearings .. .. | — | 10 | 40 | 40 | — | 3 1 | — | 3 0 | 23 2 | 29 3 0 |
| | 21 | — | Assembly .. .. | — | 10 | 155 | 155 | — | 14 6 | — | 11 12½ | — | 25 18 6 |
| | 22 | — | Testing .. .. .. | — | 10 | 90 | 90 | — | 7 2 | — | 6 15 | — | 13 17 0 |
| | 23 | — | Finishing .. .. | — | 10 | 5 | — | 0 12 | — | 0 7½ | — | — | — |
| | | | | | 20 | 25 | — | 2 18 | — | 3 2½ | — | — | — |
| | | | | | 40 | 5 | — | 0 8 | — | 1 0 | — | — | — |
| | | | | | All | — | 35 | — | 3 18 | — | 4 10 | 7 6 | 15 14 0 |
| | | | Totals .. .. .. | — | — | — | 2 285 | — | 170 13 | — | 216 17½ | 1 721 7 | 2 108 17 6 |

SUMMARIES.

*Group Hours.*

| Group | Hours | Direct labour | Factory overhead |
|---|---|---|---|
| | | £ s. d. | £ s. d. |
| 10 | 1 825 | 125 10 0 | 136 17 6 |
| 20 | 180 | 16 17 0 | 22 10 0 |
| 30 | 170 | 16 3 0 | 25 10 0 |
| 40 | 5 | 0 8 0 | 1 0 0 |
| 50 | 70 | 7 2 0 | 17 10 0 |
| 60 | 30 | 4 3 0 | 11 5 0 |
| 70 | 5 | 0 10 0 | 2 5 0 |
| Totals .. | 2 285 | 170 13 0 | 216 17 6 |

*Factory Costs.*

| | From above | Approximate analysis of material | Final analysis |
|---|---|---|---|
| | £ s. d. | £ | £ |
| Direct labour .. | 170 13 0 | 313 | 484 |
| Factory overhead cost | 216 17 6 | 332 | 549 |
| Material .. .. | 1 721 7 0 | 1 076 | 1 076 |
| Totals .. .. | 2 108 17 6 | 1 721 | 2 109 |

least, to speed up the information which they themselves require.

### Analysis of Costs.

The most important functions of the cost department are, first, to ascertain the costs of production, and, secondly, to analyse those costs. The purpose of analysing a cost is to demonstrate exactly where each item of the factory cost has been incurred, in order that it may be known where costs can be cut down, and also to provide the selling departments with data upon which to base their prices to customers who make inquiries. The designer must know the cost of the machines or apparatus which he designs, and the estimator must know the costs of previous machines or apparatus built, in order to have bases on which to make new estimates for the selling department. The management must have costs to enable them to determine what lines of machines are profitable to construct, and each of them requires the analysed costs.

Table 5 shows the cost analysis of job No. 7106, the method of compiling the costs of which was shown earlier in the paper. Only a very brief survey of the main points of this analysis is possible here.

The amount of detail shown is dependent on the amount called for, as it will be appreciated that many sub-divisions of material, labour and factory overhead costs could be given.

In this case the motor has been assembled in the motor assembly department, and the direct labour and factory overhead costs are those incurred only in this department. Thus the material figures contain, in addition to all the direct material, the labour and factory overhead costs transferred to the job from other departments.

The direct labour cost is detailed for each part as shown in Table 2.

Group 10 represents hand labour, 60 hours of which on the yoke cost £4 10s.

In group 30, 25 hours' work on the smaller machine tools costs £2 5s., while 5 hours' work on large machine tools (such as a 10-ft. planer) costs 10s.

On the yoke the labour represented by this amount would have been used in rough machining, drilling, lathe work, slotting and planing, in addition to the hand labour in filing, chipping, etc.

Cols. 7 and 9 show merely the sum of the hours worked and the money spent on each section. The factory overhead is applied as shown in Table 3. Col. 10 shows the factory overhead applied to groups, and col. 11 the total factory overhead cost for each section.

The material costs occupy col. 12, and include direct raw material drawn from the motor assembly department's stores, feeder material (including the labour and factory overhead applied to it in the feeder departments), stock parts (including labour and factory overhead), and finished parts from outside suppliers.

The totals of cols. 9, 11 and 12 are carried in one figure into col. 13, which then shows the factory cost of each section.

By applying the percentages given in Table 3 it is deduced that the total material consists, as far as this work is concerned, of

| | | £ |
|---|---|---|
| Direct material | | 1 076 |
| Feeder department and stock parts | Direct labour | 313 |
| | Factory overhead | 332 |
| | | £1 721 |

so that the eventual analysis of the factory cost is shown to be

| | £ | |
|---|---|---|
| Direct labour | 484 = | (23 per cent) |
| Factory overhead | 549 = | (26 per cent) |
| Direct material | 1 076 = | (51 per cent) |
| | £2 109 | (100 per cent) |

In addition to what has been given in this analysis, there might be shown the division of labour into day-work and piece-work (in hours and money), analysed to operations, with the factory overhead cost correspondingly divided. The "material" in col. 12 might have been split up into feeder department and other labour and factory overhead expenses, or the motor might have been further sectionalized. All of this it is possible to obtain from the data in the hands of the cost department. The example shown has been purposely kept as simple as possible, but it is sufficiently detailed to show the value of a complete cost analysis to certain of the engineering staff of a factory.

### Effect of Increased Production on Factory Overhead Expenses.

With all the data which it possesses the cost department is able to be of further service to the engineering staff. For instance, if a large demand is assured for a particular line of machines the engineers may plan a system of standardized manufacture. This should lead to increased production which, in its turn, will affect the factory overhead expenses, for, with an increase in production in any one department, while the productive labour cost will increase more or less proportionately, the factory overhead expenses will increase at a lower rate.

The overhead machine-hour rates may therefore be reduced in anticipation, which means that any one job will bear a smaller proportion of the factory overhead expenses than it did previously, and thus the factory cost will be correspondingly reduced.

### Conclusion.

The choice of a few of the many activities of a costing department which those entering upon a career in engineering should know of and appreciate, means the omission of many others which would claim the engineer's attention. It is hoped that the brief descriptions of methods and aims embodied in this paper will stimulate the necessary interest of engineers and go some way to ensure their co-operation with the cost department, the ultimate success of which is so dependent on their aid and appreciation.

# THE TESTING OF MATERIALS USED IN THE MANUFACTURE OF ELECTRICAL EQUIPMENT.

By C. Dawson, Student.

(Abstract *of paper read before the* South Midland Students' Section, 15*th November*, 1921.)

## Summary.

The following tests are described:—

*Metals.*—Tensile, compression, shearing, bending, torsion, impact, hardness, magnetic (rods and core plates), and miscellaneous.

*Insulating Materials.*
- (*a*) *Sheet and moulded insulation.*—Mechanical strength, plastic yield, electric strength, and insulation resistance.
- (*b*) *Oils.*—Electric strength, insulation resistance, viscosity, flash point, chemical reaction, and sludge.
- (*c*) *Varnishes.*—Electric strength, flexibility, acidity, and time of drying.

The procedure on delivery of material is also set out.

## Introduction.

The practice of testing all deliveries of raw materials has greatly developed during the past few years, and every large manufacturer has now a fully equipped testing department, the object of which is to detect faulty material before it passes into the shops. Otherwise a considerable amount of time and labour may be wasted. It is also an invaluable guide to the buying department.

Generally, for any given material, several sources of supply are available, and it is important to be able to distinguish the quality of the materials coming from different sources, as they may differ considerably in grade or cost, and no mere supervision of the process of manufacture, or external examination, is an adequate guarantee of quality. To ensure that the supplier understands exactly what is required of him a specification is circulated. This is merely a statement of what is, or is not, wanted and the tests which the materials will have to pass. A knowledge of any one of the following points is generally required:

(1) Is the material suitable for the purpose?
(2) Is the material good of its kind?
(3) Is the material as good as that in previous deliveries?
(4) Of two materials, equally available, which is the better?

The simplest way of determining these questions is to select samples of the material and subject them to appropriate tests, and, since a rapid and definite judgment is required, more or less arbitrary standards of quality must be accepted. Since the physical constants of a material really determine its value for constructive purposes, commercial tests may be made to approximate as closely as is practicable to tests for scientific purposes. Whenever possible, shorter and readier methods are applied.

## Metals.

Of the mechanical properties, engineers are concerned with the strength, toughness, hardness or adaptability of the metals to the mechanical operations of the workshop. To characterize these mechanical properties simple tests, such as tensile and bending tests, etc., are adopted and they suffice, except in one or two extreme cases, to detect faulty or unsafe material.

*Tensile test.*—The simplest method of performing a tensile test is to fix one end of the sample and attach weights to the other end. This is quite satisfactory where the sectional area of the sample is small, as in the case of wire, but for larger samples levers are employed so that a large load may be obtained with a small weight. Machines testing up to about 100 tons are made with a single lever and are generally used. Larger multilever machines are made, but are beyond the needs of the electrical manufacturer.

The sample should represent the average quality of the delivery, i.e. neither the best nor the worst should be chosen, but a piece which is representative of the whole. To prevent confusion the bulk and the sample should both be branded before detaching the latter. It is important that it should not be subjected to any harsh treatment such as bending, hammering or heating, as this would probably alter the properties of the sample. All samples should be of similar shape, as this may have a great influence on the results obtained. The British Standard Specifications give standard forms of test-pieces, and all these, except test-piece F, give approximately the same results. It will be noted that the gauge length is less than the parallel length. This is because with ductile materials, such as mild steel, some of the metal from the enlarged ends flows into the adjoining part of the reduced section, thus decreasing the elongation and contraction, and increasing the strength of these parts. All changes of section must be gradual to avoid uneven stressing at these points. According to the B.E.S.A. specification, if one sample does not reach the specification standard, two others should be taken and if either of these fails the delivery may be rejected.

The elongation is a measure of the permanent set and is a good criterion of the ductility of the material. For a given gauge length the elongation increases with increased diameter, so that the necessity of specifying the proportions of the test-piece is evident. Another guide to the ductility is the reduction of area, expressed as a percentage of the original area.

In the opinion of some engineers the reduction of area is a better indication of the ductility than percentage elongation, but it cannot be measured so accurately. It is also much affected by local defects and the two are in agreement only when the elongation is measured for a very short length of test-piece near the fracture. Other tests for ductility will be dealt with later.

*Examination of the fracture.*—The fracture should always be examined, as the appearance of the fractured surface is generally an index of the character of the material. The metal is said to be " crystalline " when made up of visible crystals either coarse or fine. When the crystals are too fine to be recognized as such the metal is said to be " granular," and, when very minute, " silky." Wrought iron gives a " fibrous " fracture. Cast iron is sometimes broadly classed as white or grey, according to whether the fracture is light or dark. The latter contains a higher percentage of graphitic carbon than the former. Generally, a coarsely crystalline or granular metal has less satisfactory working properties than one of the same class in which the fracture is finer. The size of grain often depends largely on the temperature at which the metal was cast, and upon the subsequent thermal and mechanical treatment and rate of loading.

The fracture of ductile materials under tension, and of brittle materials under compression, generally takes place partially or wholly by shearing, or sliding, in directions oblique to that of the direct stress. For tensile tests the shape of fracture of mild steel is a truncated cone, and it is interesting to note that the angle of the cone is always approximately 45°. In the case of cast iron, however, there is no cone, but practically a plane surface.

Cast iron is often tested in the form of beams 36 in. × 2 in. × 1 in. supported at the ends and loaded in the centre. It should not break when a load of 28 cwts. is applied, and the maximum deflection should be not less than 0·33 in. If from these results the tensile strength is calculated, the resulting figures, called the " modulus of rupture," will be higher than those obtained for the tensile test.

*Compression test.*—A table may be suspended from the shackle, below the cross-head of the testing machine, so that the sample can be crushed between the cross-head and the platform. To prevent bending, the length of the sample should not exceed two or three times the diameter. The sample is placed between hardened steel plates, and to ensure axial loading one plate is fitted with a ball joint. Hard or brittle materials generally fracture under compression by shearing across some plane oblique to the direct compressive stress. Plastic materials shorten almost without limit, expanding at the same time, and so require higher loads to effect further compressive strain. An ultimate strength is therefore difficult to specify.

*Shearing test.*—This can be carried out in a similar way to the compression test by placing the sample in a suitable holder.

*Bending test.*—The machine is set up as for a compression test, except that a plunger is fixed to the cross-head. The plunger applies the load to the centre of the sample which is supported near each end on rounded edges. By this means the sample is bent to approximately a right-angle. The load is taken off, the plunger is removed, and the sample is now placed on end and the load re-applied, and the bending continued. When a machine is not available the sample may be bent by hammering. The bending test is a rough guide as to the ductility of the material. When testing flat samples the sides should be planed, as if they are merely sheared the test is more severe and less trustworthy. The sample should, without cracking, be capable of being bent round a radius of $1\frac{1}{2}$ times the thickness of the sample until the sides are parallel. Sometimes bending tests are made while hot to detect " red shortness," i.e. brittleness when hot. Another rough, workshop test for ductility is the drifting test, in which a hole is drilled near an edge of the plate and then drifted out to a larger size.

*Torsion test.*—When a bar is fixed at one end and a couple applied at the other in a plane perpendicular to the axis of the bar, it suffers a deformation (termed torsion) which gives rise to simple shearing stresses. Tensile and compression tests give no indication as to the torsion-resisting properties of the material, and materials for shafts, etc., should therefore be subjected to a torsion test. With a special attachment this can be carried out in the tensile-testing machine previously described. The fracture of a ductile material under torsion is practically in one plane at right-angles to the axis. On the other hand, the fracture of a brittle material forms a helix of one turn returning parallel with the axis until it reaches the starting point.

*Impact test.*—Occasionally a material which satisfies the above tests will fail when subjected to shock or vibration, and it is sometimes advisable to apply an impact test. Such materials are sometimes called " fragile," as they break with little deformation and a small expenditure of mechanical work. For this reason the work done in fracturing the material is measured. An impact test is not usual in electrical work, except for some insulating materials.

*Fatigue test.*—Materials subjected to varying stresses sometimes become fatigued and fail. Special tests for this property are not usual for electrical work, as the tensile strength is also an index of the resistance to fatigue.

*Hardness test.*—There is no absolute measure of hardness and therefore comparative methods are used. The earliest method was to take various substances to find which would scratch the material under test. A modification of this is the sclerometer in which a diamond or steel point is weighted, and the weight required to produce a scratch is noted. This is more suited to brittle than to ductile materials. Another method, suited to ductile materials, is an indentation test such as the Brinell test. In this test a hardened steel ball (10 mm diameter) is forced into the material tested, generally at a polished face, by static pressure. The diameter of the impression is observed by means of a microscope, and the hardness is read off from a table which takes into account the relation between the diameter and the depth, which is the real measure in this case. For the ferrous alloys a pressure of 3 000 kg is used, and for the copper alloys 500 kg. The pressure may be applied by a dead weight, by levers, or by fluid pressure. In the Shore scleroscope a weighted conical diamond falls through a given height and the height of the rebound is noted. Different hammers are used for ferrous and copper alloys. This method is suited to finished articles as it avoids disfigurement, but the results are often influenced by the method of supporting the sample. For malleable iron it is advisable to test the sample by sawing or machining, because if not properly annealed it is liable to be harder in the centre. It should not be harder than 200 Brinell.

*Chemical test.*—The material should be machined and the drillings carefully kept and placed in a bottle, which should then be labelled and sent to the chemist for analysis. The actual work of the chemist is of little interest to the engineer but from the results obtained much may be learnt, and it is important to know the effect of the various constituents, as these indicate the properties of the material.

*Photo-micrographs.*—These are taken only in the case of faulty material or perhaps such important parts as rotor forgings and retaining rings. The microscope shows, amongst other things, the nature of any impurities, and the previous mechanical and heat treatments.

*Inspection.*—The dimensions of all materials bought to size are checked, e.g. bars and rods, wire, slate and boiler plate for switch cubicles.

*Magnetic tests.*—This branch of the subject is of growing importance because, apart from the necessity of testing for purely magnetic purposes, much work has been done of late years in connection with the correlation of the magnetic and mechanical properties. The characteristics which are of importance to the engineer are permeability, residual magnetism, coercive force, hysteresis and eddy-current losses.

The following are some of the methods of measuring permeability.

(1) *Tractional method.*—The force necessary to separate two parts of a magnetic circuit is measured as in the Thompson permeameter and Ewing's magnetic balance. These give approximate relative values. The Du Bois magnetic balance is also of this type and is more sensitive than the other examples given.

(2) *By a steady magnetic or electric action* as in Koepsal's permeameter. In principle the device is similar to a millivoltmeter in which the permanent magnet is replaced by an electromagnet, the sample under test forming part of this electromagnet. The moving coil of the instrument, carrying a small current supplied by a dry cell, takes up a position determined by the main flux. This instrument is very sensitive but is affected by stray fields. The Esterline permeameter and Ewing's permeability bridge are other examples of this method.

(3) *By measuring the increase in the electrical resistance* of bismuth when placed in a magnetic field.

(4) *By an inductive discharge through a ballistic galvanometer.*—There are several permeameters of this type, but that recommended by C. V. Burrows of the Bureau of Standards, Washington, is probably the best.*

*Hysteresis and eddy-current losses.*—In the case of core plates the losses are readily determined by means of a special transformer known as the Epstein square. The iron core is easily replaced and is formed by the iron under test. About 4·5 lb. of the iron is cut with sharp shears into strips 10 in. × 2 in., half being parallel to, and half at right-angles to, the direction of rolling. These are made up into four equal bundles, two from each direction of rolling, with press-spahn between each strip, and assembled in the apparatus. At the corners the magnetic circuit is completed with short pieces of the same or similar material bent at right-angles and interleaved between strips of adjacent bundles. A clamp is tightened over these laps to give a good magnetic joint. There are two secondaries wound under the primary, one of which is connected to a voltmeter for determining the flux (generally 10 000 lines per sq. cm). Unless an electrostatic instrument is used, a correction should be made for the current taken by the voltmeter. The other secondary is connected to the voltage coil of a low-reading wattmeter, the current coil of which is in series with the primary of the transformer. By this means the copper losses in the transformer are eliminated. For accurate work a correction may be made for the copper losses of the wattmeter potential coil. The sine-wave voltage applied to the primary is adjusted by an auto-transformer, not a resistance, until the flux is correct as indicated by the voltmeter, and then the wattmeter is read. Whenever the magnetizing circuit has been broken it should be closed through a considerable resistance, which is then gradually cut out. This prevents a large first surge and consequent high magnetization which would require subsequent demagnetization. As the hysteresis losses vary as the frequency, and the eddy-current losses vary as the square of the frequency, by repeating the experiment at another frequency the two losses may be separated.

*Conductivity.*—Copper and resistance wires should be checked for resistance.

### Insulating Materials.

*Sheet and moulded insulators.*—The most important properties of this class of material are mechanical strength, plastic yield with temperature, electric strength, insulation resistance and absence of metallic inclusions. A convenient method for comparing the strength of these materials is in the form of a cantilever, the effective length of which is 150 mm, the breadth 15 mm and the depth 15 mm. When samples are received in another form they are best compared with a standard product of the same size. Then, if the results of previous tests applied to the standard product are known, the material can be compared with any other. The plastic yield with temperature can be determined by loading the cantilever with a 2-lb. weight, placing it in an oven at 75° C. for 2 hours and noting the deflection produced with the weight removed. The temperature must be very carefully watched.

*Impact.*—The number of times which the sample may be dropped from a given height on to a concrete floor without breaking is noted, or a small Izod testing machine may be used.

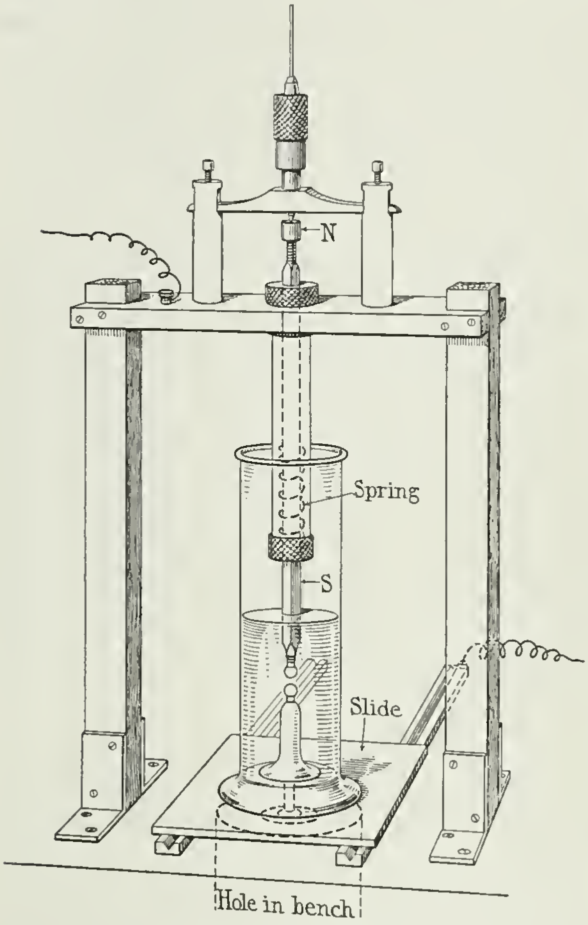
*Electric strength.*—Samples, the thickness of which is known, are placed between electrodes under a pressure of 3·5 lb. per sq. in. The secondary of an extra-high-tension transformer is connected to the electrodes and the voltage raised by varying the primary voltage by means of an auto-transformer until breakdown occurs. Some materials, e.g. ebonite, are tested under oil.

---

* See *Scientific Papers of the Bureau of Standards*, No. 117.

*Insulation resistance.*—This is determined by means of a high-voltage "Megger." If this is not sufficiently sensitive a high-voltage battery with a galvanometer and a limiting resistance in series is used.

*Metallic inclusions.*—For some materials, such as press-spahn for high-tension work, every sheet is submitted to X-rays to detect metallic inclusions.



Apparatus for testing the electric strength of oil.

### OILS.

Switch and transformer oils are obtained from crude petroleum by fractional distillation. A sample should be drawn from each barrel of oil and tested for electric strength, insulation resistance, viscosity, flash point, chemical reaction and sludge.

(*a*) *Electric strength.*—One method of testing this is shown in the figure on this page. The oil is drawn from the barrels by means of a pump or syringe kept for the purpose, and put in the glass jar, which is first rinsed with some of the oil—on no account must water be used. The bottom of the jar is drilled and a brass stud fitted. The lower electrode should be so heavy as not to be lifted by the electrostatic attraction. The jar is now placed in position by means of the sliding base. The micrometer is set at zero and the length of the spindle S adjusted by turning the nut N at the top of the spindle until the two electrodes just make contact. This is determined by means of a bell and battery. The micrometer is now turned until the required spark-gap is obtained. The bell is disconnected and the extra-high-tension leads connected up, the voltage being varied by means of an auto-transformer or induction regulator.

With spherical electrodes 0·25 in. diameter separated by 0·07 in., the oil should withstand 9 000 volts without sparking. It is very difficult to obtain consistent results when carrying out this test, and it is advisable to let the oil stand for some time after setting up the apparatus, to allow the fibres in suspension to settle. Larger electrodes with a wider gap will probably overcome this difficulty. The electric strength is greatly affected by the smallest trace of moisture and may be taken as a guide to the amount of moisture present. Another way to detect the presence of moisture is to thrust a red-hot wire into the oil. If moisture is present a crackling noise is heard, and if the oil is dry there will simply be a puff of smoke. The best method is to drop in a small piece of sodium, which decomposes any water present and liberates hydrogen.

(*b*) *Insulation resistance.*—Some engineers maintain that insulation resistance is a better criterion of the quality of the oil than the electric strength, but the difficulty is that the insulation resistance changes with temperature. The oil is placed in a jar, and disc electrodes of almost the same diameter as the internal diameter of the jar are separated by a definite amount and connected to a "Megger."

(*c*) *Viscosity.*—There are several methods of determining the viscosity, but the Redwood viscosimeter is probably the best for electrical work. The viscosity of transformer oil should not be above 850 seconds Redwood at 40° F. or it will not carry away the heat with sufficient rapidity. For oil switches the oil should not be too thin ; at, say, 70° F. the viscosity should not be less than 100 seconds Redwood, otherwise the arc will not be extinguished.

(*d*) *Flash point.*—This is the lowest temperature at which the oil gives off inflammable vapour. This should not be below 150° C. when tested in a closed testing apparatus such as Gray's.

(*e*) *Chemical reaction.*—The presence of an acid or alkali in the oil reduces the electric strength, and an alkali also gives the oil the power of absorbing moisture. To test for these impurities the oil is shaken with an equal volume of boiling water in a separator and kept at nearly 100° C. until the separation is complete, when the aqueous solution is tested. The presence of any acid or alkali is shown by adding phenolphthalein. Tincture of cochineal prepared with 20 per cent of alcohol is sometimes used, but it is too sensitive. It turns yellow if an acid is present, violet-blue if alkaline, and red if neutral. Resin is also shown in this test by its precipitation in fine, white granules at the point of separation of oil from water. The presence of sulphuric acid and sulphonates can be detected by a white precipitate forming when barium chloride solution is added. The presence of sulphur is detected by immersing copper wire in the oil and noting whether the copper blackens. Mineral impurities and additions may be tested by evaporating and igniting the oil and testing the residue.

(*f*) *Sludge.*—Sludge consists of oxidation products of the oil, which collect in and around the windings of oil-immersed transformers and choke the cooling ducts. In the case of oil switches it is not of much importance, as the growth is slow and the parts are easily accessible for cleaning. One test for sludge is to draw pure air through $100\ \text{cm}^3$ of oil heated to 150° C. in a $200\ \text{cm}^3$ flask, fitted with a condenser neck, at the rate of 3 bubbles per second (0·07 cubic ft. per hour). The deposit formed can be weighed by diluting the oil with petroleum spirit, and filtering and washing with more petroleum spirit. The deposit should not weigh more than 0·05 per cent of the original weight. A piece of bright copper having a total surface of 4·5 sq. in. must be placed in the flask during the test, as this has a catalytic action. The disadvantage with this method is the time required, viz. two days.

TABLE 1.

*Tests usually applied to the Various Materials, and Average Figures obtained.*

| Material | Tensile strength | Bend | Hardness (Brinell) | Permeability ($H = 100$) | Hysteresis and eddy currents | Miscellaneous |
|---|---|---|---|---|---|---|
| | tons/sq. in. | degrees | | | watts/lb. | |
| Rotor forgings .. | 35–45 | 180 | 170 | 180 | — | Chemical analysis |
| Rotor retaining rings | 50–56 | 180 | 250 | — | — | Chemical analysis |
| Steel rod .. .. | 33–47 | 180 | 140–200 | — | — | Chemical analysis |
| Malleable iron castings | — | — | 130–190 | — | — | Machining |
| Pig iron .. .. | — | — | — | — | — | Chemical analysis and drop test |
| Cast iron .. .. | 12–16 | — | — | 80–90 | — | Chemical analysis |
| Core plates .. .. | — | — | — | — | 1–2 | — |
| Brass rod .. .. | 30 | 72 (at least) | 80–100 | — | — | Chemical analysis |
| Brass castings .. | — | — | 60–100 | — | — | — |
| Copper (switch contacts) | — | — | 75–95 | — | — | — |
| Copper (commutator) .. | — | — | 80–100 | — | — | — |
| Copper (springs) .. | — | 75 (at least) | — | — | — | — |
| Copper wire .. .. | — | — | — | — | — | Conductivity and inspection |
| Bearing bushes .. | — | — | 70–90 | — | — | Chemical analysis |
| Solder .. .. .. | — | — | — | — | — | Chemical analysis |
| Key steel .. .. | 35–45 | — | — | — | — | Chemical analysis |

## VARNISHES.

Insulating varnishes are tested for :—

(1) *Dielectric strength.*—A layer of No. 18 S.W.G. double-cotton covered wire is wound round a brass rod, then warmed and dipped in the varnish. When dry the electric strength between the wire and the rod is determined ; this will be about 800 volts a.c. A better test is to use the impregnated paper employed in the flexibility test, for which 600 volts per mil is a fair figure.

(2) *Flexibility.*—Strips of thin paper are impregnated with several coats of varnish and stoved for several days till the paper cracks on bending it about 50 times round a radius of 0·006 in. A good varnish will withstand heating for 14 days at 130° C.

(3) *Acidity.*—Lengths of copper wire are immersed and stoved. If any acid is present the copper turns green. Another test is to add plenty of alcohol, shake and titrate with potassium hydroxide.

(4) *Time of drying.*—The time of drying the above-mentioned strips of paper is noted. Insulating varnishes stoved at 85° C. should dry overnight. Air-drying finishing varnishes dry in from 2 to 10 hours.

(5) *The effect of the varnish on the enamel* when for use with enamelled wire.

## SLATE AND MARBLE.

The dimensions of the slabs should be checked, the tolerance being $\frac{1}{16}$ in. for the larger slabs. Cracks can quickly be detected by wiping over the slab with a quickly evaporating liquid. The presence of impurities can be tested for by applying to the surface two pointed electrodes connected to a 2 000-volt transformer.

## PROCEDURE ON DELIVERY.

It is of little use to test a delivery if after the tests are complete it is found that the material has all been used, or has been mixed with the old stock. The time taken to test should be reduced to a minimum, not only on account of any inconvenience that may be caused but also to reduce the storage space. One method of fulfilling these conditions is as follows : All deliveries on arrival at the works are placed in a special store. The receipt note is made out and samples are taken for test. A description of the sample with particulars of the supplier, date, order number, works order number, receipt note number, and ultimate destination, are all entered in triplicate in a book which is sent with the samples to the testing department. The samples are here stamped with a serial number which is also entered in the book, and the particulars are noted in a book kept for the purpose. The top copy is signed and serves as a receipt to the storeman. The other two copies are torn out. One of these, a card, is handed with the samples to the man responsible for the tests. He notes on the back of the card the tests performed and, when the tests are complete, returns the card and the results of the tests to the office. The orders to the receiving stores are now written on both the card and third slip, and the third slip is returned to the receiving clerk, who initials the receipt note. The delivery, if accepted, is passed on to the stores. If the delivery does not reach the specification standard, it is generally rejected and returned to the supplier, but sometimes in special cases it may be accepted, perhaps with a proviso that it is not to be used for a certain class of work. This latter course should be used only in cases of emergency, owing to the complications introduced in the stores. The results are now typed and copies are sent to the persons interested. One copy is filed according to the material, and another, together with the card and all figures taken, is filed under the serial number.

### Conclusion.

All the plant described in the paper would probably not be installed in any one works. A suitable selection depends on the particular requirements of the works and the resulting economies that are expected. If the apparatus is also to be used for research work, as is often the case, it will be much more elaborate than if used merely for routine testing. Much work has been done in connection with the testing of metals, and the various tests have been standardized. Little progress has been made, however, in regard to the insulating materials, and every manufacturer has his own standards; but this state of affairs will probably be remedied in the near future.

---

# PROCEEDINGS OF THE INSTITUTION.

## 686th ORDINARY MEETING, 2 NOVEMBER, 1922.

(Held in the Institution Lecture Theatre.)

**Mr. J. S. Highfield,** Past-President, took the chair at 6 p.m.

The minutes of the Annual General Meeting of the 25th May, 1922, were taken as read, and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

The following donations were announced as having been received and the thanks of the meeting were accorded to the donors :—

*Benevolent Fund :* F. W. D. Adcock ; Anonymous ; C. T. Allan ; W. F. Andrews ; A. G. Barnard ; J. E. Baty ; H. P. Bearcroft ; C. A. Beaton ; P. L. Bernstein ; J. E. Betley ; C. G. Bevan ; L. Birks ; W. Birmingham ; H. E. Blackiston ; W. H. Bray ; R. V. Broberg ; W. Brownlie ; E. A. Buxton ; H. G. Cameron ; A. S. Campbell ; P. G. Campling ; G. W. Carpenter ; F. D. Chadwick ; S. K. Chatterjee ; J. C. Clarke ; J. R. Clayton ; G. D. Clegg ; H. W. Cockerill ; R. L. Cribbes ; A. F. Cross ; C. F. Crymble ; T. E. Daniel ; J. F. Davie ; H. O. Davies ; J. N. Deas ; A. C. de Oliveira ; The Diesel Engine Users' Association ; G. W. Dumbrell ; W. Duncan ; F. J. Edgar ; G. J. Evans ; A. R. Everest ; L. J. B. Forbes ; C. F. Fowler ; C. S. Franklin ; J. R. Gardiner ; E. L. Glew ; J. R. W. Grainge ; F. W. Green ; J. D. Green ; J. G. Griffin ; E. Halton ; C. Hamilton ; F. Harris ; H. H. Harrison ; A. T. Harrop ; F. de B. Hart ; R. S. Hobson ; E. H. Hooper ; J. W. Horner ; W. Howes ; P. R. Hughes ; V. R. Hurle ; W. H. M. Kelman ; P. C. Kerr ; C. D. King ; F. A. Lawson ; T. F. Lee ; A. E. McColl ; F. C. Meaby ; A. P. Mitchell ; F. Morton ; J. Mullin ; A. R. Murray ; J. Y. Nelson ; C. A. Newell ; W. H. Parker ; L. W. Phillips ; E. A. K. Picard ; H. V. Pointon ; F. C. Porte ; S. C. Price ; C. W. L. Ray ; W. J. Rickets ; A. J. Roberts ; A. S. Robertson ; E. G. Ross ; A. Rushton ; J. Russell ; A. H. Selwyn ; J. W. Slorach ; J. L. Smith ; E. Steadman ; A. Stewart ; W. G. Stock ; D. Stringfellow ; C. F. Thomas ; H. J. S. Thomas ; G. Thompson ; J. A. Troughton ; E. O. Turner ; F. Walker ; L. G. Walker ; H. K. Whitehorn ; H. W. Wilkinson ; E. Williams ; J. C Wrighton ; The " Twenty-Five " Club ; Western Centre (per W. Collins).

The following letter, dated 29th October, was read from the President of the French Society of Electricians :—

DEAR MR. PRESIDENT,

The invitation which you have sent me, on behalf of the Institution of Electrical Engineers, to attend their Meeting on the 2nd November is highly appreciated by the French Society of Electricians as a mark of sympathy and scientific esteem, coming from the illustrious Society over which you preside and addressed to a younger Society which is endeavouring to serve science and industry as well as its country and Allied Nations. I deeply regret not being able to come to London to express to you personally, in the name of the French Society, the cordial feeling of the French electricians towards their colleagues of the United Kingdom and to hear the instructive address which you propose to give. I beg you to convey to the members of the Institution an expression of the warm esteem of their French colleagues and to accept for yourself, Mr. President, my cordial and fraternal sentiments.

(*Signed*) M. BRILLOUIN.

The Premiums (see vol. 60, page 528; also *Institution Notes*, No. 34, page 25, August 1922) awarded during the session 1921–22 were then presented by the Chairman to such of the recipients as were present.

**The Chairman:** I now have great pleasure in asking the new President, Mr. Frank Gill, to take the chair.

The chair was then vacated by Mr. J. S. Highfield and taken by **Mr. Frank Gill** amid applause.

**Mr. Roger T. Smith:** It is my privilege to propose a vote of thanks to our retiring President who, in common with his predecessors, will look back upon his year of office with mixed feelings. First of all, the retiring President feels very much as a boy does when he leaves school and goes home for the holidays, and perhaps that is the predominant feeling. I believe that most Presidents—and certainly I know that Mr. Highfield had that feeling—soon after their installation in the chair come to feel that perhaps the greatest possession which the Institution has is its tradition. We in this country cherish our great traditions. We date our civil liberties from the time of King John and, although the electrical industry cannot boast of such an age, the Institution of Electrical Engineers has 50 years of tradition to give it ballast. Perhaps Mr. Highfield will agree that the most interesting events in his year of office were the Commemoration Meetings to celebrate that 50 years' existence. During those Meetings and the social functions which made them so pleasant he was unfortunately confined to his house. Possibly the greatest tribute to his complete understanding of the things and people which go to make up tradition, was the fact that before he fell ill the arrangements made were so complete and so entirely in the proper spirit that, in spite of his absence, the Commemoration Meetings were completely successful. During his period of office not only did he maintain the traditions of the Institution, but he added to them. To give only one instance, I would refer to the way in which, after months of very arduous toil, he succeeded in persuading Mr. Oliver Heaviside to accept the Faraday Medal. Without the President's unfailing courtesy and patience I do not think that this Institution would have had the pleasure of honouring, however late, that very remarkable man. I beg to propose: "That the best thanks of the Institution be accorded to Mr. J. S. Highfield for the very able manner in which he has filled the office of President during the past year."

**Mr. Ll. B. Atkinson:** It is with very great pleasure that I second the resolution proposed by Mr. Roger Smith. When, at the end of last Session, I handed over the reins of office and vacated the chair in favour of Mr. Highfield, I expressed my full anticipation of the results that would be obtained under his leadership, and I am sure everybody will agree with Mr. Roger Smith that the past Session has been one of the most interesting and enjoyable that it has been our lot to have. Every Session has its problems and its own special tasks, and I should like to refer to one of them, i.e. the completion and dedication of the Institution War Memorial. There are, of course, in an Institution like this, many different thoughts on such subjects, but I think that the War Memorial in its design and wording, and the dedication ceremony in its form and sentiment, were sufficiently wide to cover all the various shades of thought. Those larger matters to which Mr. Roger Smith has referred and which come to the view of the general membership are, as it were, only the peaks in the midst of a very large amount of work which the President has to perform. The ordinary daily work of the Institution involves discussions and decisions which have to be taken daily and hourly by the President on behalf of the members, and there are many occasions when it is very easy to make a mistake which will mar the work of the Institution and destroy its usefulness and popularity among its members. The tact and judgment which the President has shown on those smaller matters as well as on the larger ones have been a great asset to the Institution, and I have much pleasure in seconding the resolution.

**The President:** Before I formally put this vote to the Meeting, I should like to pay my tribute of admiration to our retiring President. I have seen a good deal of him during the past Session and I have seen that with untiring energy and great ability he has devoted himself to the furtherance of the progress of the Institution. With patience and tact he has dealt with the affairs of the Institution, both in the Council and out of the Council, and he leaves the chair not only with very greatly added respect, but with something which I venture to think is much more valuable—the affection of those whose pleasure it has been to work with him during this past year.

The resolution was then put by the President and carried with acclamation.

**Mr. J. S. Highfield:** It is very difficult to thank you all for your very kind, your very hearty response to this resolution; indeed it is difficult to say anything after the very kind things that have been said this evening. Mr. Roger Smith said that he felt like a schoolboy when he had given up the office of President; I am not at all sure that I did not feel rather like a schoolboy throughout the whole year. I do not remember a more pleasant year; it was spoilt only by the illness which prevented my attendance at our Commemoration Meetings. It is necessarily pleasant to act as helmsman to this great Institution. It is an

Institution in which I think its members every year individually take greater pride, and its efficiency and influence have been increasing for years past. A good deal was accomplished in the year, thanks in a great measure to the fact that we had become thoroughly re-established in our own building, and also to the way in which everyone helped and worked in the interests of the Institution. The Past-Presidents, particularly the two immediate Past-Presidents, Mr. Roger Smith and Mr. Ll. B. Atkinson, gave help at all times; and it is due to the four Vice-Presidents that the Commemoration Meetings were so admirably conducted and, in addition, there were Members of Council serving manfully on the many Committees. I should also like to mention the Chairmen of the Local Centres and of the Committees who worked very hard and accomplished much. I should like specially to refer to the Chairman and the Committee of the Scottish Centre, and I am sure all the members who took part in the Scottish Meeting will long remember it as a most delightful and useful time. It only remains for me to thank the Secretary and his staff for all the help they gave. They were to me a complete, thoroughly efficient working crew, and all I as helmsman had to do was to take charge of the helm and leave them to do the rest. In conclusion I should like to wish Mr. Gill all the success as our President which I know he will achieve.

**The President** then delivered his Inaugural Address (see page 1).

**Sir John Snell :** I should like as my first duty to add to what has been said by our immediate Past-President in offering our congratulations to Mr. Gill on becoming President of this Institution, but I should also like to congratulate the Institution itself upon the appointment as President of one who is a master of his subject. The Address is one of more than national importance, dealing as it does with what the President has happily termed the "transportation of intelligence"; it is perhaps even more than one of Imperial importance because it is cosmopolitan and is on a subject of immense value to the present state of highly organized civilization. Some 10 years ago the President and I were engaged in a very lengthy duel, which entailed our attendance in a stifling court and proved very exhausting to both of us. Sitting there day after day, hearing Mr. Gill unfold the technicalities of the case which he was defending, I became more and more imbued with a deeper and deeper respect for him. After those laborious days, when the judges and others had retired during the long vacation, it fell to the lot of Mr. Gill and myself to sit down day by day to try to arrive at a certain valuation which was entrusted to us. On the one side there was a man who was a master of his subject, who knew every detail from complicated telephone switchboards and large multicore cables down to what are commonly known as "potheads," and on the other side a man who had a most superficial knowledge and who had to rely on the able engineers of the Post Office for their assistance, but Mr. Gill did not take the slightest advantage of this fact throughout the whole of that difficult technical negotiation. My respect for him, which had deepened during those laborious days in Court, reached its acme when we had concluded that work of ours in the long vacation. I suggest that the Address to which we have listened to-night is of the greatest importance, and I think it is more pleasing perhaps to the Institution that, after a succession of Presidents who have represented more particularly the power side of engineering, we should now have an Address representing what is generally known as the weak-current side, delivered by one who has his subject at his finger-ends. The weak-current side is one of increasing importance to the whole world, and one which has not reached in Europe that degree of excellence which it has reached in the home of its birth, the United States. It has become a highly technical branch of our industry. Those who have watched the almost uncanny working of an automatic telephone would agree with me there. It is pleasing to think that we now have amongst our Presidential Addresses a paper dealing with long-distance communication. I commend the paper to the members of the Institution and I beg to move "That the best thanks of the Institution be accorded to Mr. Frank Gill for his interesting and instructive Presidential Address, and that, with his permission, the Address be printed in the *Journal* of the Institution."

**Sir Richard Glazebrook :** I am privileged to second the proposal that has been so ably put before you by Sir John Snell, and I think I need add little to what he has said as to the merits and the work of our President and the importance that we attach to the fact that he is now President of the Institution and in a position to give us something of the vast stores of his knowledge on this very complicated and difficult subject. I would ask you to thank him for his Address, not merely for the Address itself but for the high ideals that he put before us as to the manner in which he would undertake the work of President and in which we as members should discharge our duties, and for his realization of the importance of those duties. One could spend a long time in discussing the advantages to civilization derived from the work of engineers, and there are few details of that work that have added more to the advantages of life and to the progress of civilization than the improvements in the method of communication about which we have heard so much this evening. We thank him for the instructive character of the Address, which has been really instructive in many ways. We all have some idea of the complication of telephonic communication, the difficulties that must occur, and the problems that the telephone engineer has to solve, but I think that our knowledge—my own at least—has been comparatively small, and I believe that few of us realized all the skill and thought that must have been put into the development of telephony as we now know it and as it is in the United States. In other ways I think the Address is instructive because it has put clearly before us the great importance of this problem of long-distance telephony and has indicated some methods by which a solution of the problem in Europe might be possible.

The resolution was then put to the meeting by Mr. J. S. Highfield, Past-President, and was carried with acclamation. After the President had briefly replied, the meeting terminated at 7.35 p.m.

# OBSERVATIONS OF THE FIELD STRENGTH OF HORSEA WIRELESS STATION.*

By E. B. Moullin, M.A.

(*Paper received* 18*th September*, 1922.)

## Summary.

Many measurements are recorded of the strength at Cambridge of the signals from Horsea during September 1921, in which the Vallauri method of measurement was employed. The field strength is deduced from the measured E.M.F. of the signal, the effective height of the receiving aerial being determined experimentally both from the distribution of current in the aerial up-lead, and by comparing the receptive power of the aerial with that of a loop. Incidentally, the measurements of effective height provide a very accurate verification of the law that for short distances the E.M.F. set up in an aerial is in direct proportion to the frequency of the incident waves. It is found that at a wave-length of 3 000 m the Horsea signals suffer in their journey an absorption of 40 per cent, and evidence is produced of a regular diurnal variation of intensity. The accuracy of the aural method of comparison is discussed, and the feasibility of making long-distance measurements with a visual indicator, instead of by aural comparison, is pointed out.

## Table of Contents.

(1) Introduction.
(2) Method of measuring the received E.M.F.
(3) Description of the aerial used, and the method of building up the equivalent circuit.
(4) Production and measurement of the local E.M.F.
(5) Method of adjusting the circuits and making comparisons.
(6) Tables of measured E.M.F.'s.
(7) Measurement of the effective height of the aerial.
(8) Field strength produced by Horsea, and the correction factor for absorption.
(9) Probable accuracy of aural comparison, and evidence of diurnal variation of signal strength.
(10) Comparison of measurements made with different mutual inductances.
(11) Conclusion.

## (1) Introduction.

In August, September and October, 1921, the Naval Wireless Station at Horsea, Portsmouth, carried out a series of regular continuous-wave transmissions. Information of the tests was kindly afforded to the author by Mr. L. B. Turner, of the Wireless Telegraphy Commission, and advantage was taken of this excellent opportunity to make systematic observations of the field strengths. The transmissions were on wave-lengths ranging from 2 500 m to 8 000 m, and were distributed throughout a continuous 24 hours at intervals of a few days.

The author's experiments described in the paper were made during the end of August, early September and early October at Cambridge, which is situated 177 km N.E. by N. of Horsea. This distance is among the longest recorded of the short-distance overland tests, and it was hoped that the measurements could be used as a still further test of the Hertz formula, without any correcting factor for absorption. The results, however, show field strengths some 40 per cent less than the value given by the Hertz formula, owing to absorption by the intervening land and obstructions. The path from Horsea to Cambridge lies over the Portsdown Hills, the hills near Guildford and, finally, after a long stretch of flat, open country, over the low chalk hills near Baldock, some 15 miles from Cambridge. During the whole period of the measurements the weather was exceptionally hot and fine, and had been so for the previous three months.

## (2) Method of Measuring the Received E.M.F.

The method employed was a slight modification of the well-known comparison method due to Vallauri. This system of signal measurement has often been described, but may be briefly summarized as follows:

Two identical receiving loops are provided having their planes at right-angles to one another, and oriented so that the effect produced in one is a maximum, and in consequence a minimum or zero in the other. The receiving circuit with its amplifiers and detectors can be connected at will to either loop, and a local E.M.F. of the same frequency as the incoming signal and of adjustable and measurable value can, when desired, be introduced into the circuit comprised by the receiver, and the loop that is inappreciably affected by the incoming signal. It will be understood that there are two circuits identical in every respect, in one of which is situated an E.M.F. produced by the incoming electromagnetic waves radiated from a distant transmitting station, while in the other is situated an E.M.F. of the same frequency but produced by a local generator.

If the local E.M.F. produces the same current in its associated circuit as the signal E.M.F. produces in the other circuit, then, the circuits being identical, the locally produced E.M.F. is equal in value to the E.M.F. produced by the incoming signal. The signal E.M.F. having been determined in this way, the field strength can be calculated from the linear dimensions of the receiving loop.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

The currents produced by either E.M.F. can be measured and compared by using a thermo-junction, by measuring the rectified current produced by a valve connected across part of the circuit, or by comparing the sounds produced in a telephone connected to this rectifier: the choice of method depends mainly on the magnitude of the current to be measured.

The difficulties of the Vallauri method of measurement are well known, but probably only fully recognized by those who have actually performed the operation. The two main difficuties are (1) comparing the effect of the signal and local E.M.F., and (2) the measurement of the local E.M.F. The former difficulty is most accentuated when audible comparison has to be resorted to. If the incoming waves are broken up into Morse signs, then audible comparison is the only satisfactory method, but it is unfortunately under these circumstances that audible comparison becomes most difficult. If the transmitting key is held down it is easy to match perfectly the note of the local signal with that of the incoming signal, the condition necessary both to ensure that the local E.M.F. is of the correct frequency and to make accurate comparison possible. But when Morse signs are being received, as was the case with the Horsea transmissions, it is in general impossible to match their note with that of the locally produced Morse signs nearer than a semitone; this is possibly due to the transmitting station and local generator having different decrements, even though the two receiving circuits have the same decrement. Any small difference of note entails constant worry as to whether the local generator is adjusted to the correct frequency.

The difficulties attendant upon the measurement of the local E.M.F. are those involved in designing suitable means (e.g. inductive, capacity or resistance coupling) for introducing it into the required circuit, and more especially in effectively screening, both magnetically and electrically, the whole of the local generator circuit in order to ensure that no E.M.F. is introduced except through the known and desired path.

The author's experiments differ from those of Vallauri in that instead of using two suitably oriented loops, the incoming signal produced an E.M.F. in a small, flat-topped aerial; the local E.M.F. was introduced into an equivalent circuit built up so as to have the same electrical constants as the actual aerial, but of linear dimensions so small that the effect upon it of the incoming signal was infinitesimal.

### (3) DESCRIPTION OF THE AERIAL USED, AND THE METHOD OF BUILDING UP THE EQUIVALENT CIRCUIT.

The aerial employed consisted of two parallel wires 1 m apart and 21 m long, stretched parallel to the ground at an average height of $5\frac{1}{2}$ m. Each conductor consisted of two No. 20 S.W.G. copper wires stranded together, and the steady-current resistance of the whole was about 0·25 ohm. The earth connection was to a water pipe close to the receiver.

The aerial was supported at one end from the gable of a house and at the other by an earthed, tubular-steel mast, the clearance at each end being about 1 m. The arrangement of the up-lead can be seen from Fig. 5.

The static capacity of the aerial was found by a bridge measurement to be $310\,\mu\mu$F. The natural wave-length was not accurately determined, but would probably be about $4\frac{1}{4}$ times the total length of wire or, say, 150 m. Extrapolation from a curve connecting wave-length and inductance inserted in the aerial indicates that the fundamental was about 170 m: the total inductance of the aerial must have been between $30\,\mu$H and $60\,\mu$H.

The circuit used for receiving is shown in Fig. 1. The inductance $L$ was fixed and equal to $2\,000\,\mu$H $\pm$ 2 per cent, and the capacity $C$ varied between $600\,\mu\mu$F for $\lambda = 2\,500$ m up to $3\,400\,\mu\mu$F for $\lambda = 5\,000$ m. The resistance of L ranged from 26 ohms at $3 \times 10^5$ periods per sec. down to 14 ohms at $1{\cdot}5 \times 10^5$ periods per sec. (steady-current resistance 13 ohms).

A triode rectifying by curvature of the anode-current characteristic was employed for detecting, with the grid 4-volt negative to prevent decrement due to grid current. Any form of retro-action was carefully avoided, and a separate heterodyne used to render the signals audible.

It was assumed that the circuit of Fig. 1 with a distributed E.M.F. in the aerial could be replaced by the circuit shown in Fig. 2 acted upon by a concentrated E.M.F. produced by the generator G.

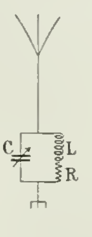


FIG. 1.

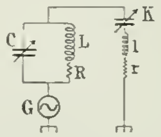


FIG. 2.

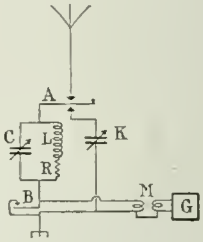


FIG. 3.

If $L$ is greater than $l$ and $C$ greater than $K$, the condition which makes the P.D. across L as great as possible for a given E.M.F. supplied by the generator is, to a close approximation, given by

$$\omega^2\left\{L(K + C) + Kl\right\} = 1$$

For the values of $L$, $l$, $K$ and $C$ employed, this expression is correct to about 0·2 per cent. It was found that, with $l$ omitted from the circuit of Fig. 2, the value of $K$ required to tune the circuit of Fig. 2 to the same frequency as the actual aerial circuit in Fig. 1, ranged from $220\,\mu\mu$F for $\lambda = 2\,000$ m up to $270\,\mu\mu$F for $\lambda = 6\,000$ m. Introducing a small inductance first in the aerial up-lead, and then in series with K, seemed to change the frequency of both circuits by the same amount; it was in consequence considered that no appreciable error would be introduced by omitting $l$ from the equivalent circuit. If $l/L$ is about 1/20, then it is easy to show that $K$ is about 5 per cent greater than it would have been if $l$ had not been omitted. It was hoped that it would have been possible to find the appropriate value of $r$ by comparing the sound produced in the telephones when the same local

E.M.F. was introduced in turn into the true aerial circuit and into the equivalent circuit; but the circuits appeared to be so nearly equal, even with $r$ entirely omitted, that it was decided not to attempt to replace the resistance of the aerial. It can be shown that the presence of a resistance $r$ in the equivalent circuit reduces the P.D. across $L$ in the ratio

$$\frac{R(K+C)}{K} \text{ to } \left\{ \frac{rK}{K+C} + \frac{R(K+C)}{K} \right\}$$

It can be seen from this expression that with the values of $K$ and $C$ in use, the presence of $r$ does not appreciably reduce the P.D. across L unless $r >> R$. By using a form of the author's thermionic voltmeter* to determine the P.D. across L, it has subsequently been found that a given E.M.F. produced a P.D. across L 15 per cent greater in the equivalent circuit than in the actual aerial circuit. The table of Section 6 shows the value of the signal E.M.F. as actually determined without allowance for the aerial resistance, and also the value corrected by 15 per cent.

### (4) Production and Measurement of the Local E.M.F.

A triode oscillator completely enclosed in a metal case, placed about 6 ft. away from the receiver, was used as the local generator. The E.M.F. was introduced from this generator into the equivalent circuit by means of mutual inductances the values of which could be calculated. The generator current passing through the primary of these mutual inductances was measured by a 1-ohm vacuo-thermo junction and reflecting galvanometer, the junction being calibrated with direct current. The mutuals used, four in number, took the form of two co-axial circles of fine wire with planes parallel and placed about 0·5 cm apart. The calculated values were as follows: $M_1 = 0{\cdot}180\,\mu$H; $M_2 = 0{\cdot}48\,\mu$H; $M_3 = 0{\cdot}78\,\mu$H; and $M_4 = 0{\cdot}24\,\mu$H. The current through the primary of these mutuals was varied by altering the output of the triode generator by means of a variable-resistance box (shunted by a condenser) placed in the anode circuit: a more convenient method would probably have been to shunt the primary of the mutual inductance itself with a variable resistance.

### (5) Method of Adjusting the Circuits and Making Comparisons.

The aerial circuit and the equivalent circuit used are shown in Fig. 3. By depressing the key A the aerial was replaced by the condenser K, and by depressing the short-circuiting key B the local E.M.F. could be introduced into the aerial or into the equivalent circuit.

Having picked up the incoming signal and adjusted the condenser C until the sound produced in the telephones, actuated by the rectifier connected across L, was a maximum, the heterodyne was adjusted until the beat note became so low as to be inaudible. The frequency of the local generator G was then adjusted until, with the keys A and B depressed, the beat note between it and the heterodyne became inaudibly low; the local generator and the incoming signal were then sensibly of the same frequency. The heterodyne was then altered so as to give a fairly high-pitched note with the signal: fine adjustment was then made to the frequency of G to match its note to the signal. This method of adjustment was found in practice to be the most reliable, and prevented any chance of having the frequency of G as much above the heterodyne as the signal was below, or vice versa. On a few occasions the Horsea key was held down for a short space at the end of a sending period, and more than once it was found that the Horsea note and the local note caused beats of only a few periods per second, which seemed to justify the method.

Having made a preliminary adjustment of the output of G, the telephones were moved off the ears, or the detecting triode dulled, until the Horsea signals were on the limit of audition. G was then finally adjusted until the local signals were also just audible.

Having noted the current through the primary of the mutual inductance, a second mutual inductance of very different value was substituted for the first, and the comparison repeated. Occasionally, when time permitted, a third measurement was made with a third mutual inductance.

The importance of these check measurements is twofold.

(1) If the two measurements are not in fairly close agreement, it shows that the mutual inductance is not the only path through which the local E.M.F. is being introduced.

(2) If previous experiments have shown that the local generator is effectively screened, then a check is made on the accuracy of the comparison, at best a difficult operation.

Between 23rd August and 2nd September, 1921, 37 measurements were made, all of which were useless owing to defective screening. The various causes of unsuccessful screening were traced out one by one, until on 4th September measurements with three mutual inductances showed that success had at last been achieved.

The following examples are given to show that the E.M.F. was introduced through the desired path, and to show also that the comparison can be made with an accuracy of at least ± 10 per cent. $I$ denotes the current through the primary of a mutual inductance $M$.

4th September. $\lambda = 4\,500$ m; $M_1I_1/M_2I_2 = 1{\cdot}08$
21st October. $\lambda = 3\,000$ m; $M_2I_2/M_3I_3 = 1{\cdot}12$

On 7th September a comparison was made with a signal produced by a local continuous-wave generator, with key held down to aid comparison, the result being that with $\lambda = 3\,000$ m, $M_1I_1/M_2I_2 = 1{\cdot}12$.

The author would suggest that in measuring signal strengths it would be an advantage to make a general practice of using several mutual inductances, or some equivalent plan of obtaining check measurements; there could then be no doubt that the measured E.M.F. was a fair approximation to the signal E.M.F.

---

* See paper read before the Wireless Section, 6th December, 1922; also *Wireless World*, 1922, vol. 10, p. 1.

TABLE 1.

| Date and time | Trans-mitting current | Wave-length | $M_2I_2$ | $M_3I_3$ | Received E.M.F. (= $\omega MI$) | Received E.M.F. (× 1·15 to correct for aerial res.) |
|---|---|---|---|---|---|---|
| **19/10/21** | A | m | μH × mA | μH × mA | mV | mV |
| 2000 | 50 | 4 500 | 0·48 × 12 = 5·76 | — | — | — |
| **21/10/21** | | | | | | |
| 0750–0800 | 51 | 3 000 | 0·48 × 16·7 = 8·00 | — | 5 | 5·6 |
| 1500–1522 | 48 | 3 000 | 0·48 × 16·7 = 8·00 | — | 5 | 5·6 |
| 1538–1600 | 49 | 3 000 | 0·48 × 16·0 = 7·70 | — | 4·85 | 5·3 |
| 1900–1922 | 49 | 3 000 | 0·48 × 16·0 = 7·70 | — | 4·85 | 5·3 |
| 1938–2000 | 50 | 3 000 | — | 0·78 × 8·4 = 6·6 | 4·1 | 4·7 |
| 2100–2122 | 49 | 3 000 | 0·48 × 15·1 = 7·25 | 0·78 × 8·0 = 6·2 | 4·55 or 3·9 | 5 or 4·5 |
| 2138–2200 | 50 | 3 000 | 0·48 × 14·6 = 7 | 0·78 × 8·0 = 6·2 | 4·4 or 3·9 | 5 or 4·5 |
| | | | Mean 7·6 | Mean 6·3 | 4·8 or 4·0 | 5·5 or 4·6 |
| *Reversion to incorrect circuit for check purposes.* | | | | | | |
| 1500–1522 | 48 | 3 000 | 0·48 × 5·5 = 2·65 | 0·18 × 8·9 = 1·6 | — | — |

TABLE 2.

| Date and time | Transmitting current | Wave-length | $M_1I_1$ | $M_2I_2$ | $M_4I_4$ |
|---|---|---|---|---|---|
| **6/9/21** | A | m | μH × mA | μH × mA | μH × mA |
| 0700–0722 | 37 | 2 500 | — | — | 0·24 × 9·3 = 2·24 |
| 0900–0922 | 37 | 2 500 | — | 0·48 × 6·7 = 3·2 | 0·24 × 9·7 = 2·34 |
| 1100–1122 | 37 | 2 500 | — | 0·48 × 6 = 2·9 | — |
| 1300–1322 | 38 | 2 500 | — | 0·48 × 5·7 = 2·75 | 0·24 × 8·6 = 2·05 |
| 1500–1522 | 39 | 2 500 | — | — | 0·24 × 7·5 = 1·8 |
| 1700–1722 | 42 | 2 500 | — | — | 0·24 × 7·7 = 1·85 |
| 1900–1922 | 40 | 2 500 | 0·18 × 9 = 1·56 | — | — |
| 2100–2122 | 38 | 2 500 | 0·18 × 9 = 1·56 | 0·48 × 4·2 = 2 | — |
| | | | Mean 1·56 | Mean 2·7 | Mean 2·05 |
| **11/10/21** | | | | | |
| 1900–1922 | 37 | 2 500 | 0·18 × 8·4 = 1·5 | 0·48 × 4·3 = 2·05 | — |
| 2100–2122 | 38 | 2 500 | 0·18 × 7·5 = 1·35 | 0·48 × 4·0 = 1·90 | — |
| **14/10/21** | | | | | |
| 1910–1922 | 52 | 2 500 | — | 0·48 × 5·0 = 2·40 | — |
| **11/10/21** | | | | | |
| 2140–2200 | 36 | 3 000 | 0·18 × 9·5 = 1·66 | 0·48 × 3·5 = 1·68 | — |
| **14/10/21** | | | | | |
| 1945–1955 | 50 | 3 000 | — | 0·48 × 5·0 = 2·40 | — |
| 2145–2200 | 51 | 3 000 | 0·18 × 9·8 = 1·76 | 0·48 × 4·7 = 2·20 | — |
| **18/10/21** | | | | | |
| 2115–2122 | 45 | 3 000 | 0·18 × 8·5 = 1·52 | — | — |
| 2145–2200 | 45 | 3 000 | 0·18 × 8·1 = 1·48 | 0·48 × 4·5 = 2·15 | — |
| **4/9/21** | | | | | |
| 2015–2045 | 48 | 4 500 | 0·18 × 10·5 = 1·9 | 0·48 × 3·5 = 1·70 | — |
| **5/9/21** | | | | | |
| 2015–2045 | 50 | 4 500 | 0·18 × 10·6 = 1·9 | 0·48 × 5·0 = 2·40 | 0·24 × 7·1 = 1·7 |
| **6/9/21** | | | | | |
| 2015–2045 | 50 | 4 500 | 0·18 × 9·8 = 1·76 | 0·48 × 4·2 = 2·00 | — |
| **7/9/21** | | | | | |
| 2015–2045 | 50 | 4 500 | 0·18 × 10·5 = 1·9 | 0·48 × 4·6 = 2·20 | — |

### (6) Tables of Measured E.M.F.'s.

On 19th and 21st October, 1921, 12 measurements were made, and are shown collected in Table 1.

Between 4th September and 18th October, 1921, 33 measurements were made, and are shown collected in Table 2.

The signal E.M.F. cannot, unfortunately, be deduced from the values given in Table 2. Owing to a misconception, a mistake was made in the equivalent circuit, K being placed in parallel with C instead of in series with L and C in parallel: the E.M.F.'s obtained from Table 2 differ from the signal E.M.F. by some constant dependent on the values of C and K. The readings, though useless for determining the values of the signal E.M.F., are perfectly valid for comparison purposes.

### (7) Measurement of the Effective Height of the Aerial.

In order that the value of the incident magnetic or electric field may be deduced from the measured E.M.F. in the aerial, the effective height of the aerial must be determined.

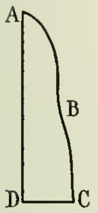
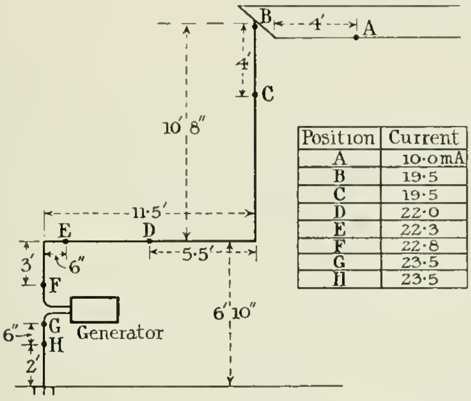


Fig. 4.



| Position | Current |
|---|---|
| A | 10·0 mA |
| B | 19·5 |
| C | 19·5 |
| D | 22·0 |
| E | 22·3 |
| F | 22·8 |
| G | 23·5 |
| H | 23·5 |

Fig. 5.

Suppose the distribution of current in the up-lead of the aerial to be as shown in Fig. 4; then the aerial is equivalent to a uniform vertical current of height equal to (area ABCD/CD). In the case of an aerial having a large-capacity top, the equivalent height approximates closely to the actual height of the roof. Under the ideal conditions of a perfectly conducting earth and of no local screening due to currents induced in surrounding objects, the effective height of the aerial would be equal to the equivalent height as defined above.

The equivalent height of the aerial under consideration was measured by plotting a curve of current distribution in the up-lead, determined by placing a thermo-junction at the points marked A, B, C, D, E, F, G and H in Fig. 5. The resulting curve of current distribution is plotted in Fig. 6. That a large-capacity top is indeed successful in producing a sensibly uniform current in the up-lead is readily seen from this curve, which shows that the equivalent height (4·8 m) is 90 per cent of the actual height.

As the bottom 2 m of the up-lead were inside a house, it seemed probable that the effective height would be less than 4·8 m, on account of local screening. The effective height was determined by comparing the E.M.F. set up in the aerial with that set up in a loop; the transmitting station being the same in each case and situated 1 000 m N.W. of the aerial.

The comparison was not made audibly, but by using a form of the author's thermionic voltmeter actuated through a two-stage amplifier connected across the aerial tuning inductance.

The method of measurement consisted in noting the voltmeter deflection produced by the incoming signal, and then introducing into the earth lead an E.M.F. of the same frequency and adjusting its magnitude until the same voltmeter deflection was produced. In this way, as with the Aldebaran experiments of the Marine Française, the local E.M.F. is introduced into the actual aerial circuit, and there is no necessity to produce its equivalent.

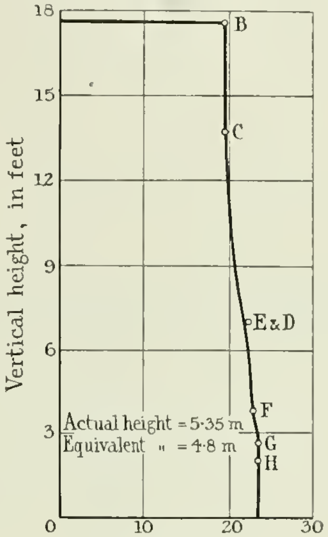


Fig. 6.

The local E.M.F. was not introduced through the medium of a mutual inductance, but by means of a resistance potentiometer constructed from fine Eureka wire, the current through the potentiometer wire being measured by a sensitive vacuo-thermo junction. This system has many advantages to offer over the mutual inductance method, first because it is easier to construct a small resistance than to construct a small mutual inductance of the value required; secondly, the measurement of very small mutuals is a matter of no little difficulty, and few formulæ are available for calculating the values of a variable mutual inductance of suitable size and dimensions. The resistance potentiometer is readily made with a slide wire so as to be completely adjustable. The local E.M.F. can then be adjusted by varying the slide rather than by the amount of current passing through it. Check measurements can be performed, as with a fixed mutual inductance, by making two measurements with different slide currents.

The signal E.M.F. produced by 0·42 A in the sending aerial was measured at wave-lengths of 1 920 m and 1 020 m, also at 1 020 m with 0·23 A in the sending aerial. The results are shown collected in Table 3. Each of the three tests was repeated six times, and the values tabulated are the mean of the six readings: in no case did a reading depart more than 2 per cent from the mean value given.

Fig. 7 shows voltmeter deflections plotted against the value of the locally impressed E.M.F. This curve was taken directly after the test at 1 920 m wave-length, and, as it is a straight line through the origin, it shows that no E.M.F. was introduced through any other path but the potentiometer. Similar curves, equally good, were taken after each of the 1 020 m wave-length tests.

TABLE 3.

| Wave-length | Transmitting current | Mean voltmeter reading | Received E.M.F. | $\lambda E/I_s$ |
|---|---|---|---|---|
| m | A | V | mV | |
| 1 920 | 0·4 | 1·01 | 1·11 | $5{\cdot}35 \times 10^3$ |
| 1 020 | 0·42 | 1·63 | 2·15 | $5{\cdot}25 \times 10^3$ |
| 1 020 | 0·23 | 1·45 | 1·2 | $5{\cdot}3 \times 10^3$ |

*Note.*—The amplifier adjustment was different in each case.

Table 3 shows that for the same transmitting current the received E.M.F. varies inversely as the wave-length, and that the E.M.F. for the same wave-length varies directly as the transmitting current. This shows that, at any rate between 1 000 m and 2 000 m wave-length, the effective receiving height is independent of frequency.

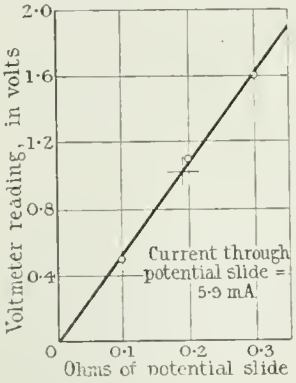


FIG. 7.

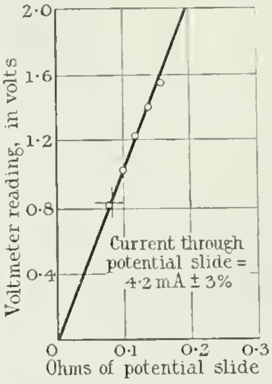


FIG. 8.

The receiving loop was constructed by removing one of the two wires forming the top of the aerial, and bringing a wire from the far end down the mast and back again along the ground to the instruments.

The current in the transmitting aerial was 0·43 A at a wave-length of 1 020 m, and the mean voltmeter reading from seven signals was 0·83 V, with a maximum departure of 2 per cent from the mean.

Fig. 8 shows voltmeter readings plotted against local E.M.F. (as in Fig. 6), from which it may be seen that the signal E.M.F. was 0·34 mV.

The E.M.F. set up in an aerial from an aerial is given by the formula

$$E_a = \frac{188 h_s h_r I_s}{\lambda d} \text{ volts,}$$

and the E.M.F. set up in a loop from an aerial is given by the formula

$$E_l = \frac{1\,184 h_s I_s A \cos \alpha}{\lambda^2 d} \text{ volts}$$

where $A$ is the area of the loop and $\alpha$ is the angle between the plane of the loop and the direction of the transmitting aerial.

If ${}_1I_s$ is the sending current when receiving on the aerial, and ${}_2I_s$ is the sending current when receiving on the loop, $\lambda$, $d$ and $h_s$ being the same in both cases, we have

$$h_r = \frac{E_a}{E_l} \cdot \frac{1\,184 \times {}_2I_s A \cos \alpha}{188 \times {}_1I_s \lambda}$$

In the particular case considered $A = 130$ m², $\alpha = 35°$, and $\lambda = 1\,020$ m, hence $h_r = 4{\cdot}25$ m.

The effective height is thus found to be 89 per cent of the equivalent height and 80 per cent of the actual height.

The loop being formed from the aerial, the screening effects obtaining in each case are the same. It was impossible to erect a transmitter in the direction of Horsea, but as the ground in the immediate vicinity was more open in the Horsea direction than in the opposite direction towards the transmitter, the value found for the effective height is more likely to be slightly too low than the reverse.

## (8) FIELD STRENGTH PRODUCED BY HORSEA, AND THE CORRECTION FACTOR FOR ABSORPTION.

Table 1 shows that at 3 000 m wave-length the E.M.F. set up by Horsea in the aerial at Cambridge was between 4·6 and 5·5 mV, the effective height of the receiving aerial being 4·25 m. This corresponds to a field strength of about 0·012 mV per cm.

It is believed that the Horsea aerial has a capacity of 4 900 $\mu\mu$F, that the height of the roof is about 130 m, and that the effective height is 113 m.*

Under ideal conditions of a perfectly conducting earth and no absorption of the wave from any causes, the electric field intensity set up is given by the formula

$$E = \frac{60\pi h_s I_s}{\lambda d} \text{ volts per cm}$$

In the present case $d = 178$ km, $\lambda = 3\,000$ m, and $I_s = 50$ A, so that the electrical intensity under such conditions would be 0·02 mV per cm; the intensity actually measured is exactly 60 per cent of the ideal. At a wave-length of 4 500 m and the same transmitting current, the electric intensity would be 0·0136 mV per cm. The E.M.F. measured for this wave-length (on 19th October, 1921) was 2·9 mV, corresponding to 0·007 mV per cm, so that the correction factor for absorption is in this case 0·52.

---

* For these figures, and for the values of the sending currents, the author is indebted to H.M. Signal School, Portsmouth, through the Wireless Telegraphy Commission.

A correction factor of as much as 0·6 for such a comparatively short overland transmission may seem rather surprising, but is nevertheless not without precedent. The experiments of Reich in 1913 between Cologne and Göttingen[*]—a distance of 216 km—show a correction factor of 0·61 at a wave-length of 3 000 m, and a correction factor of as much as 0·4 at 2 000 m wave-length. Austin[†] records a case of a transmission at 1 000 m wave-length over a distance of 83 km over land, in which the correcting factor was 0·45. In both the cases cited above the method of measurement was with a thermo-element placed in the aerial. It is of interest to note that the Austin-Cohen formula for oversea transmission gives a correction factor of 0·86 and the Fuller formula about 0·88. By comparison with these a correction factor of 0·6 for overland transmission does not seem unduly great.

It would be interesting to discover whether the absorption is due mainly to the passage over the first (hilly) half of the path. If measurements of Horsea could be made at the National Physical Laboratory, or some station in that vicinity, they would be very instructive in this respect.

TABLE 4.

| Date and time | Wave-length $\lambda$ | Transmitting current $I_s$ | $M_1I_1$ | $M_2I_2$ | $M_1I_1/I_s$ | $M_2I_2/I_s$ |
|---|---|---|---|---|---|---|
| **11/10/21** | m | A | | | | |
| 2100–2122 | 2 500 | 38 | $0{\cdot}18 \times 7{\cdot}5 = 1{\cdot}35$ | $0{\cdot}48 \times 4 = 1{\cdot}9$ | 350 | 500 |
| **14/10/21** | | | | | | |
| 1910–1922 | 2 500 | 52 | — | $0{\cdot}48 \times 5 = 2{\cdot}4$ | — | 460 |
| **11/10/21** | | | | | | |
| 2140–2200 | 3 000 | 36 | $0{\cdot}18 \times 9{\cdot}5 = 1{\cdot}66$ | $0{\cdot}48 \times 3{\cdot}5 = 1{\cdot}68$ | 460 | 465 |
| **14/10/21** | | | | | | |
| 1945–1955 | 3 000 | 50 | — | $0{\cdot}48 \times 5 = 2{\cdot}4$ | — | 480 |
| 2145–2200 | 3 000 | 51 | $0{\cdot}18 \times 9{\cdot}8 = 1{\cdot}76$ | $0{\cdot}48 \times 4{\cdot}7 = 2{\cdot}2$ | 345 | 430 |

### (9) PROBABLE ACCURACY OF AURAL COMPARISON AND EVIDENCE OF DIURNAL VARIATION IN SIGNAL STRENGTH.

The observations given in Table 2 cannot, unfortunately, be used to determine the value of the field strength, because, as explained before, they give the value of the E.M.F. required to produce the correct copy of the signal in a circuit that was not the correct copy of the aerial; they are too small in some ratio depending on the frequency. This ratio can be determined for the case of the 3 000 m wave, because there were many observations made with both the correct and the incorrect circuit. Unfortunately, as no more signals of 2 500 m wave-length were sent, the conversion factor could not be found for this wave.

The observations of Table 2, though useless for the actual determination of signal strength, are nevertheless perfectly valid for analysing the probable accuracy of aural comparison, and for comparing signal strengths on different days or during the passage of a single day.

Reference to the Horsea log (obtained several months after the measurements were finished) shows that there were only two occasions measured on which the sending currents differed appreciably.

These occurred on 11th and 14th October, and the results are given in Table 4 for ease of comparison.

It will be seen from this table that the E.M.F. measured varies almost exactly as the transmitting current: the extent of the departure from the mean value indicates that the accuracy of the aural comparison must be of the order of ± 5 per cent. In the case of Vallauri's measurements there is a departure of about 12 per cent from the mean in each group of signals recorded. The observations of the press signals ($\lambda$ = 4 500 m) on each of four consecutive nights show a variation of 5 per cent from the mean.[*] So as to minimize risk of subconsciously adjusting the local generator until the galvanometer reading coincided with the previous observation, the galvanometer was re-suspended and the scale distance altered before the measurement of the press signal on 5th October, and calibrated after the determination of the signal E.M.F. In spite of these alterations the observations on 4th and 5th October agree very closely. With the same end in view the filament and anode voltages of the local generator were several times altered in order to change the relation between the output of the generator and the adjusting resistance placed in the anode circuit (see Section 4).

In each of the two all-day observations (on 6th September and 9th October, respectively) the extent of the departure of observed E.M.F. from the mean value found seems to have some relation to the hour of observation.

The percentage variation from the mean, plotted against time of observation for these two days, is shown in Fig. 9. It can be seen that the variations from the mean do not occur in a random manner like mere errors of observation. In the early part of the day the signals are always stronger than the mean, and vice versa; also the two curves, taken six weeks apart, have the same general characteristics. The difficulties and errors inherent to aural comparison are too great to allow very much reliance to be placed on these curves of temporal variation of signal strength; but they nevertheless suggest that a regular diurnal variation is observable even over comparatively short distances, such as 100 miles. Further observations on this point would be of much interest.

---

[*] *Physikalische Zeitschrift*, 1913, vol. 14, p. 934.

[†] *Bulletin of the Bureau of Standards*, 1911, vol. 7, p. 315.

[*] See Table 2.

### (10) Comparison of Measurements made with Different Mutual Inductances.

Tables 1, 2 and 4 show that the measurements of the same signal with different mutual inductances never agree exactly; that of 0·48 $\mu$H is always from 20 to 30 per cent greater than that of 0·175 $\mu$H, and 20 per cent greater than that of 0·77 $\mu$H.

This discrepancy naturally suggests that there was some other small path by which some part of the signal was introduced, but the author believes that this was not the case, for the following reasons. First, tests were made repeatedly to see if the local E.M.F. was audible without the introducing key B (Fig. 3) being pressed; in no case could any sound whatever be heard on the equivalent circuit, and only a very slight trace on the actual aerial. Secondly, the mutual inductance leads were occasionally crossed over and this second determination was always in complete agreement with the first.

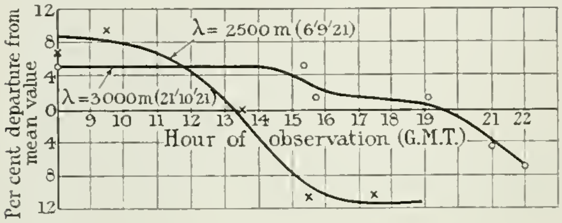


Fig. 9.

The discrepancy is presumably due to the calculated value of the inductance being incorrect (probably due to more than one turn being used), or else to the existence of a capacity coupling in addition to an inductive coupling between the coils of the mutual inductance.

The value of each mutual inductance has been measured and found to be approximately the same as that calculated, but the possible accuracy of the measurements was not sufficient to determine with certainty the ratio between them.

The formula used for calculating the value of the mutual inductance is

$$M = 4\pi a\left(\log_e \frac{8a}{d} - 2\right)n_1 n_2 \text{ cm}$$

where $a$ is the radius of the circle,
$d$ is the distance between the planes of the two circles, and
$n_1$ and $n_2$ are the number of turns in each coil.

Particulars of the four mutual inductances are given in Table 5.

### (11) Conclusion.

Although aural comparison is undoubtedly capable of yielding consistent results, it is a most difficult, laborious and tiring operation. Now that thermionic valves are so perfect and easy to use it seems almost unnecessary to resort to aural comparison, since a visual apparatus can be readily arranged and used. Examples of both methods have been given in the paper, and the accuracy and advantages of the indicator method are too obvious to need detailed description: the absence of the necessity for a heterodyne is in itself a tremendous gain.

For measuring extremely weak signals the aural method may be the only one available, but that the visual method is capable of considerable sensitivity the following example will make clear.

It has been seen that it is easy to measure an E.M.F. of only 0·5 mV in an aerial of very high resistance; greater sensitivity can of course be obtained by using more than a two-stage amplifier, but the measurements then become difficult unless the amplification is obtained by several aperiodic stages. If, as has been suggested,* a balanced rectifier is used as the final indicator instead of a direct-calibrated thermionic voltmeter, an additional sensitivity of at least 50 times can be obtained.

Table 5.

| Designation of mutual inductance | $a$ | $d$ | $n_1$ | $n_2$ | Value |
|---|---|---|---|---|---|
| | cm | cm | | | $\mu$H |
| 1 | 3·75 | 0·63 | 2 | 1 | 0·180 |
| 2 | 3·75 | 0·32 | 2 | 2 | 0·48 |
| 3 | 6 | 0·5 | 2 | 2 | 0·78 |
| 4 | 2·9 | 0·38 | 3 | 1 | 0·23 |

If an aerial 42 m high (10 times the height of the Cambridge aerial) is available, by no means an impossible height for a ship aerial, then, according to the Fuller formula, Horsea with a wave-length of 6 000 m would produce in it an E.M.F. of 0·25 mV at a distance of 2 500 miles. Consequently it is possible to proceed right across the North Atlantic with a visual indicator and measure continuously the signal E.M.F. from even a comparatively small station like Horsea.

Should an expedition be arranged for the purpose it could hardly fail to get most valuable and accurate information on the relation between absorption and distance and also on twilight effects.

---

* E. B. Moullin and L. B. Turner: "The Thermionic Triode as Rectifier," *Journal I.E.E.*, 1922, vol. 59, p. 706.

# TELEPHONIC REPEATERS AND LONG DISTANCE TELEPHONY.

By J. A. Cooper, Student.

(Abstract *of paper read before the* South Midland Students' Section, 17*th January*, 1922.)

## Summary.

The paper reviews the development of long-distance telephony and shows the great improvements effected by the introduction of telephonic repeaters employing thermionic valves.

Improvements of greater importance introduced up to April, 1921, when the paper was written, were made by the use of the microphonic transmitter, hard drawn copper wire, loading, cable balancing, phantom circuits and the triode repeater.

The repeater is defined and is shown to have the following advantages: it increases the telephonic range and makes possible the use of finer wire or underground cable. From a consideration of the theory of the triode it is shown that hard valves are preferred because of their longer life and greater stability.

Post Office tests for magnification, speech, stability, life and characteristics are described, and results of some experiments are given.

An account of the Edison, single-relay and double-relay systems is given, and the difficulties encountered in their designs are indicated. The double relay is shown to be preferable on the grounds of adaptability and simplicity.

Results are given, indicating that if repeaters were inserted at intervals equivalent to 15 miles of standard cable or telephone lines an improvement of 15 to 20 m.s.c. would be brought about.

With regard to cost it is stated that a single repeater costs £50 a year to maintain but leads to economy, e.g. a saving of £15 000 a year on London's main trunk lines alone.

Some indication is given as to the probable development of long-distance telephone systems. A forecast of 50-lb. trunk lines, and transcontinental and transoceanic telephony is made.

References are given in the Appendix.

## Introduction.

The telephone engineer regards his long-distance circuits as long-distance power-transmission lines. These lines may vary in length from 2 000 miles to (theoretically) infinity. Unlike ordinary power lines the telephone circuit carries a current of varying frequency, the frequency depending upon the speaker's voice. Again, a few micro-watts are sufficient to actuate a telephone receiver, and to obtain this power at the receiving end a few milli-watts must be generated by the transmitter. An efficiency of less than 1 per cent is indicated. In dealing with a telephone line five factors have to be considered, viz. resistance, insulation, capacity, inductance and its liability to cause, or be affected by, cross-talk and other outside disturbances.

All these factors are intimately connected with each other. For obvious reasons telephone lines have to be run very close together, and this leads invariably to mutual induction or cross-talk. It is of the highest importance that cross-talk shall be eliminated and contractors have to make sure that: "In any completed section of (balanced telephone) cable, the amount of cross-talk between any two circuits shall not exceed that due to 40 millionths of the current entering the cable at the sending end as measured on a standard cross-talk meter." On overhead telephone lines, and in unbalanced cable circuits, the cross-talk may be 10 times as great as that on unbalanced cables. However careful the contractor may be, cross-talk is inevitable unless the current generated by the transmitter is kept at a low value. Hence the importance of resistance and insulation.

Insulation is also made important by the fact that, if it is faulty, noises on the telephone will result.

Capacity attenuates the amplitude of the telephone speech currents. To avoid this, inductance may be added, but the addition of inductance also implies the addition of impedance, so that only a certain amount is allowable.

There is a sixth factor, which the lay mind would probably hold to be of first importance, namely cost.

Copper *must* be used for telephone wires, and because of this, if for no other reason, heavy wires cannot be used in order to reduce the resistance.

Some of the difficulties which have always confronted telephone engineers having been indicated, it is of interest to consider how they have been overcome. The problems of increasing the range and reducing the cost of the telephone have been studied for over 40 years. Improvements have, up to the present time, been made in six stages. The original Bell telephone was limited in its range of operation by the small amount of current generated by the transmitter. The first developments were the introduction of the microphonic transmitter and improvements in the receivers. Then, in the late 'eighties, hard drawn copper wire came to be used, and our chief cities and London and Paris were soon linked up by telephone. Telephone engineers first sought to eliminate transmission losses and to make their lines efficient.

Ten years' experience brought them to the third stage, viz. the introduction of "loading," i.e. the insertion of inductance into the telephone circuit. Loading may be of two kinds, (1) coil loading, and (2) continuous loading. Coil loading is the introduction into the circuit of coils of wire wound, as shown in Fig. 1, upon a soft-iron core. These coils are introduced at carefully calculated intervals on long lines, their number and spacing depending on the nature and length of the circuit. Continuous loading is effected by the winding of soft iron wire or strip over the copper conductor before annealing.

Annealing coats the iron with a light film of oxide, and so to some extent insulates it from the wire. Continuous loading is not quite as efficient as coil loading, but both are important.

Loading made speech practicable over three or more times the distances previously possible. In 1913 the fourth stage of development was reached, when cable balancing, which will be referred to later, was introduced. Quickly following it came the introduction of the thermionic valve incorporated in the telephone repeater, and, concurrently, came the discovery of "phantom circuits" which, it has been found, may be coil-loaded and fitted with telephone repeaters. When two separate circuits are used, each as a conductor, a phantom circuit is produced. The first two circuits are known as "physical" circuits. Thus, four physical circuits give rise to a total of seven circuits, three phantom circuits being possible, since two may be utilized to produce a third.

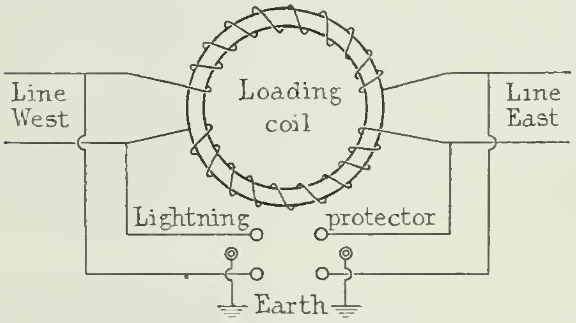


FIG. 1.—Coil loading.

At the present moment phantom circuits, repeaters and cable balancing are being rapidly developed, and experiments are being made with "wired wireless." Two comparisons will serve to indicate the progress that has been made. Our first long-distance telephones worked over distances of 100 to 200 miles. To-day it is possible to telephone to San Francisco from New York, a distance of 3 400 miles. Loading and repeaters have made this distance equivalent to 60 miles of standard cable.* The original telephone wires weighed 800 lb. per mile. The New York-Chicago cable is an aerial cable weighing 9 lb. per foot, and is $2\frac{5}{8}$ inches in diameter.

It is supposed to contain 206 pairs of conductors, the weight of which does not exceed 40 lb. per mile, and may be as low as 20 lb. It follows a circuitous route of over 800 miles.

### TELEPHONIC REPEATERS.

Having sketched the development of long-distance telephony, the author will now refer in some detail to telephonic repeaters. A telephonic repeater is an apparatus consisting of transformers, batteries and a thermionic valve, and is used for amplifying and re-transmitting currents along telephone lines. It has three great advantages: (1) It makes telephony possible over long distances; (2) it enables smaller gauge wire to be used for speech currents; and (3) it makes the use of underground cables possible for long-distance telephony.

It is obvious that no mechanical relay can possibly be used in a telephone circuit, since it would involve a time-lag. The relayed current must have the same form as that produced by the transmitter. Therefore the only types of relay possible are those in which speech currents are used to modify a magnetic or electric field. Magnetic control has twice been tried, but has not been developed commercially.

Electric control has proved more successful. The simplest example is the Cooper-Hewitt circuit, in which a mercury-vapour discharge tube is used in series with a high-tension battery and transformer secondary. The speech currents flow through the transformer primary and set up a large increase in the tube circuit, which is used to operate the receiver.

The thermionic valve invented by Dr. J. A. Fleming has, however, superseded all other forms of relay. If a body be heated to or above a temperature of 1 500° C. the force of cohesion between its electrons is overcome and some are emitted. If it be enclosed in a lightly exhausted globe, and if a positively charged plate be also enclosed in the globe at a little distance from the hot body there will be a flow of electrons to the positively charged body. If the difference of potential between the two be maintained at a sufficiently high value, the electrons will acquire so high a velocity that they will split up into positive and negative ions any molecules of gas with which they may come into contact. The latter will increase the flow of current between the hot body and the plate, but the positive ions will disintegrate the hot body by their bombardment. Since the hot body is usually a filament, the disintegration shortens the life of the valve considerably. The valve is rendered unstable also by the absorption of the residual gas molecules by (probably) the glass, and the vacuum is thus increased.

It is obvious, therefore, that soft valves cannot be made or maintained identical in any quantity. By reason of their greater stability and longer life, hard valves have come to be used most widely in repeaters. These have a vacuum of $10^{-8}$ mm of mercury, and, by suitably treating the parts, can be made very stable since occlusion is prevented and ionization is impossible. They are capable of a greater power output than soft valves, and are independent of the external temperature. The modern valve contains three electrodes, the third, known as the "grid," being perforated and placed between and insulated from the filament and plate. If a negative charge be placed on this grid it will repel the electron flow and prevent it reaching the plate. If it be positively charged it will assist the flow to the plate. Varying charges on the grid will clearly result in varying filament-plate currents. The speech currents in the telephone circuits are transformed up and used to vary the grid potential.

---

* Standard cable is a dry-core paper-insulated lead-covered cable, the wires of which have a loop resistance of 88 ohms per mile, an average mutual capacity (wire-to-wire) of 0·054 $\mu$F per mile, and an average insulation resistance of not less than 200 megohms per mile between wires.

Two equations may be given here. The first is due to Professor O. W. Richardson and is

$$N = aT^{-\frac{1}{2}}e^{-b/T}$$

where $N$ = number of electrons emitted per square centimetre of hot body per second;
$a$ and $b$ are constants; and
$T$ = absolute temperature of the body.

The second is due to Dr. Langmuir and is

$$I = A(V + Bv)^{3/2}$$

where $V$ = voltage of plate, due to the high-tension battery;
$v$ = voltage of grid, due to the grid battery; and
$A$ and $B$ are constants depending on the construction of the valve.

It is clear from this second equation that if $v$ is maintained negative by the grid battery, small changes in current value transformed up will cause large changes in the value of $v$, and hence of $I$, the plate current.

### Soft Valves and Telephonic Repeaters.

Four types of soft valves have been applied to telephonic repeaters and tested by the Post Office, namely, the audion, Leiben-Reisz, Round and Post Office low-vacuum valves.

*Audion.*—This consists of a three-stage resistance amplifier. The speech currents are stepped up by a 25 : 1 transformer and are used to vary the potential of the first of three valves in cascade. The high-tension battery supplies 50 volts and the high-tension current is used to operate the receivers through a 4 : 1 step-down transformer.

*Leiben-Reisz relay.*—This relay has two unique features. The anode and cathode are 4 inches apart instead of the usual $\frac{1}{4}$ inch or $\frac{1}{2}$ inch. A small quantity of mercury amalgam is enclosed in the coolest part of the tube and is used: (*a*) to reduce the resistance of the discharge path by mercury vapour; (*b*) to maintain constant pressure; and (*c*) to carry the electrons and avoid occlusion. The valve is used in a circuit similar to that employed for the present-day hard valve, with the exception that the high-tension circuit has a resistance in it which limits the discharge.

*Round valve.*—Two important properties of this valve are: (1) The plate surrounds the grid, which again surrounds the filament, and in this way the electrification of the glass is said to be prevented; and (2) a small piece of asbestos surrounded by a heater coil is used to soften the vacuum when required.

*Post Office low-vacuum valve.*—This is similar to the Round valve, but is larger, with a view to obtaining greater magnification with ordinary speech currents.

TABLE 1.

| Type of Valve | Magnification | Speech Tests | | | Stability | Lag | Life, in hours |
|---|---|---|---|---|---|---|---|
| | | Improvement | | Articulation | | | |
| | | One direction | Duplex | | | | |
| | | m.s.c. | m.s.c. | | | | |
| Audion | Output does not bear a definite relation to input | 8 (with 1 valve)<br>25 (with 2 valves)<br>30 (with 3 valves) | 10 | Good | Very stable | Nil | 1 000 (given by makers) |
| Leiben-Reisz | Test not made as valve unstable | — | 22 | Good when valve adjusted | Very unstable | 15 mins. | 1 000 (given by makers) |
| Round | Good | 28 | 22 | Good | Very stable | 3 secs. (increasing with age) | Upwards of 600 |
| Post Office low vacuum | Large | 25 to 30 | — | Good | Good | Nil | 200 to 500 |
| P.O. hard | Greater than with soft valves | — | 25 | Very clear | Extremely stable | Nil | Not tested longer than soft |

### Post Office Tests on Valves.

The valves have been subjected to five classes of tests.

(1) *Magnification.*—This is the ratio of "Output of the relay, in micro-watts" to "Input to the relay, in micro-watts." To test the magnification an alternator is used to supply current at speech frequency, and a non-reactive resistance absorbs the amplified current. The results are expressed graphically.

(2) *Speech tests.*—These are made on from 30 to 50 miles of standard cable. The transmission efficiency is compared with a direct circuit, (*a*) with, and (*b*) without, the repeater working. The difference between (*a*) and

(*b*) gives the improvement due to the relay, expressed in miles of standard cable. The improvement is measured with the repeater working (*c*) in one direction, and (*d*) in both directions.

(3) *and* (4) *Stability and life tests.*—The repeater is run continuously until the valves burn out or until the efficiency falls below a certain value.

Periodical tests are made to ascertain the efficiency and the stability of adjustments.

Table 1 gives the results of Post Office tests.*

Lag tests are made to determine the time required to reach full efficiency after the filament battery has been switched on. This time should be very short so that (1) the filament is lighted only while speech is taking place, and (2) the life of the valve shall not be shortened by useless burning.

(5) *The d.c. characteristic* is determined and recorded as a graph. To obtain the points for this graph the currents across the input secondary and output primary are measured by means of a reflecting galvanometer for varying grid potentials brought about by a potentiometer. The galvanometer records on a sensitized paper attached to the potentiometer sliding contact.

Results of tests made with a hard valve in 1917 are given in the table, together with those made with soft valves.

### Hard Valves in Telephone Repeaters.

The Post Office is at the present time using hard "French" valves almost exclusively in its repeaters. Two forms are being tried—the B.T.H. valve and a valve in which the grid and plate are both spirals of wire (enabling them to be thoroughly heated during manufacture to expel occluded gas). The advantages of hard valves have already been enumerated. There are two disadvantages which, however, do not outweigh the advantages. They are: (1) The high vacuum gives the filament-grid circuit a very high resistance and so makes the design of the input transformer difficult; and (2) the amplified current being greater than that with soft valves there is greater liability to cross-talk.

### Types of Repeater Circuits.

There are two types of repeater circuit—the single relay and the double relay. Both are modifications of the Edison repeater system, in which the speech currents pass through the primary of a transformer and induce currents in the secondary and relay circuits. The microphone is actuated and produces strengthening currents in the secondary of its induction coil. These currents are led to the centre of the transformer primary and, if the impedances of the lines on the two sides are equal, they do not affect the receiving coil.

*The single-relay repeater.*—The way in which the Edison system has been modified for use with a valve is shown in Fig. 2. It is important to notice that this system requires two conditions, (1) the division of the amplified current at the centre of A, and (2) lines electrically equal on each side of A. These conditions are great drawbacks in a single-repeater circuit. Thus, if more than one repeater be used in a circuit, unless the transmission losses between the repeaters absorb the amplified current which is "reflected back" from each repeater there will be an "echo" effect and repeaters will re-amplify and re-transmit the currents already amplified in the repeater ahead on the line, thus making speech impossible. Again, if only one repeater be used, condition (2) requires that either (*a*) the repeater shall be at the electrical centre of the telephone line, or (*b*) an accurate artificial balance shall be arrived at for the lines on each side of A. These requirements are very difficult to obtain in practice, but unless they are obtained the valve circuits will oscillate, and the valve will "howl" and drown all speech. Consequently the single-relay repeater is very little used, being confined to underground cable circuits, since aerial circuits cannot be balanced.

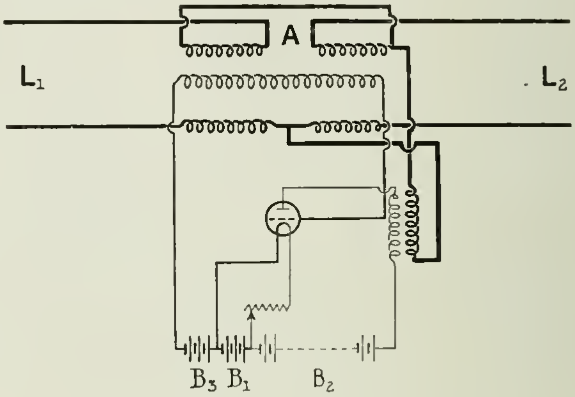


Fig. 2.—Single-relay repeater (1916).

A modification of the single-relay repeater is worthy of consideration, but the author is not aware that it has yet been tested commercially. It has been developed by Herr van Kesteren, a Dutch telegraph engineer. His scheme of connections is shown in Fig. 3. Imagine the speaker to be at X′ and the person spoken to at Y′. X′ is connected to X and Y′ to Y either (*a*) through a direct, single pair of wires, or (*b*) through a transformer. Speech currents arriving at X divide, one portion passing through the amplifier A and on to Y and the other being stopped by the amplifier B. The first current will continue beyond Y and tend to return to X, so that it is essential, in order to avoid "echo" or "reflection," that the circuit shall be sufficiently long, to enable any excess current to be absorbed by the transmission losses. So long as this is the case the circuits are stable and, as no balancing is required, the repeaters can be made highly efficient. With such a four-wire circuit the weight of trunk lines in the British Isles might be reduced to 20 lb. per mile, if loaded and supplied with repeaters at intervals of 50 miles. Theoretically there is no limit to the distances over which speech may be made possible by the van

---

* In this table all the values under the heading "Life" are only approximate. The life given by the makers is probably only a rough value, and the author has no information as to how they make their tests. They make no statement as to the rate of change of efficiency during life tests, so that some part of that life may be of no practical value. The Round valve was not given a fair test as to its life, and the Post Office low-vacuum valve was run at a high rate while under test and would probably show a higher value under fairer conditions.

Kesteren system. Experiment has shown that it will reduce a circuit 90 m.s.c. in length to 15 m.s.c. (further reduction would result in "echo"). Speech over a distance equivalent to 15 m.s.c. is loud. Now, New York to San Francisco is a distance equivalent to not more than 60 m.s.c. without repeaters (the actual distance is 3 400 miles). This shows that loud speech over a distance of, say, 5 000 miles is a practical proposition and, since the four wires necessary may be comparatively thin, cost is not a prohibitive factor. There are practical difficulties, however, which make it doubtful if the widespread introduction of a four-wire trunk system is practicable at the present time, although there is a wide range of application open to it. The system has the disadvantage that, unless a four-wire junction is available when two van Kesteren circuits are to be joined together, the total impedance will make them equal to the sum of their standard cable equivalents. In the case of the balanced system with double-relay repeater (to be described later) this is not so.

Whether the van Kesteren system will ever be used commercially on a large scale is a matter of opinion. The author gathers that British Post Office electrical engineers are more in favour of the development of more perfect balance in the double-relay repeater. This relay has the great advantage that it can be introduced into the existing metallic circuit system without requiring the erection of new lines.

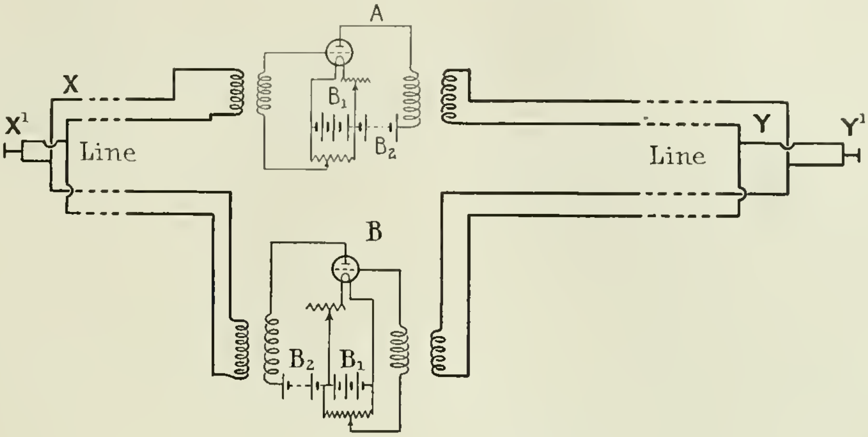


Fig. 3.—Van Kesteren's system.

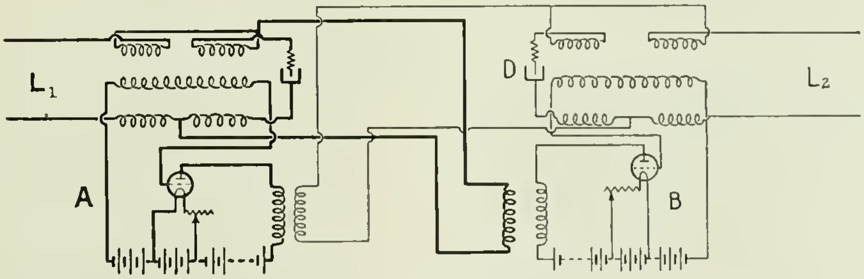


Fig. 4.—Double-relay repeater.

*The double-relay repeater.*—A diagram of a double-relay repeater is given in Fig. 4. It will be seen that it consists essentially of two single-relay repeaters with the addition of two artificial balancing circuits. The incoming speech current is amplified by one valve and passed on to the outgoing circuit through a transformer in the plate-filament circuit. As in the single-repeater circuit, the current divides in the line transformer of the second relay and passes partly through the line balance and partly along the line. The "up" and "down" circuits are separated by the repeater and, if the artificial balances are made and maintained accurately, "howling" will be impossible. Due to this arrangement it is probable, however, that there will be different efficiencies in different directions. The artificial balances referred to are combinations of resistance, capacity and impedance arranged to reproduce exactly the electrical conditions and qualities of the lines to which they are connected. They are designed from the results of experiments and calculations made at the repeater stations. The method of calculation is given in Professor A. E. Kennelly's book on "The Application of Hyperbolic Functions to Electrical Engineering Problems."

The efficiency of the double-relay repeaters depends largely upon the design of the transformers, the ratio of transformation of which depends upon the impedance of the line and the apparent resistance of the valve.

Since this resistance is very high the number of turns in the transformer secondary is also very high for maximum efficiency, but too great a number leads to a reduction in the clearness of articulation owing to capacity effects in the windings. Attention has already been drawn to this disadvantage. The double relays also suffer from the disadvantages of multiplicity of apparatus, and it is not possible to signal through them by means of a magneto without supplying additional relays. However, the Post Office hopes to evolve a system of signalling in which a current of such frequency will be employed that the repeater will transmit signals as it does speech currents. Such a system would minimize both delays and the quantity of apparatus necessary.

Some few figures in connection with the present-day repeater may be of interest. The ratio of the input (step-up) transformer is 40 : 1, and that of the output (step-down) transformer 10 : 1. The heating battery is an 8-volt accumulator supplying 0·9 ampere per valve. The high-tension battery is of 200 volts with an electron flow of 1–5 mA per valve. This battery, similarly to the 5-volt grid battery, may be of dry cells or small accumulators.

*Results.*—The improvement effected by repeaters depends upon the electrical length of the line. A long line, i.e. one equivalent to more than 15 m.s.c., has a lighter load than a short one and correspondingly greater sensitiveness. In this case the improvement may be equivalent to from 25 to 32 m.s.c. Short lines with their heavier loads and lack of balance (implying lack of sensitiveness in the repeater) give an improvement of from 12 to 17 m.s.c.

It has been calculated that if repeaters could be inserted at intervals of 15 m.s.c., and the lines could be satisfactorily adjusted, an improvement of from 15 to 20 m.s.c. would be brought about.

The New York–Chicago and the New York–San Francisco telephone lines have already been referred to.

## COST.

The question of cost is an important one. It has been estimated that a repeater costs £50 a year to maintain. This is a higher figure than for loading but the improvements are far greater. The first cost is negligible by comparison with the savings effected in line costs. The heaviest item is due to attendance, but a second estimate is to the effect that two attendants could easily look after 100 repeater circuits, so that this item should not be very heavy. On the other hand, it may be possible to save £15 000 annually by the introduction of repeaters into main trunk lines radiating from London. As old telephone lines become obsolete and are replaced, the advantages of the use of repeaters should become apparent in Post Office estimates.

## CONCLUSION.

Post Office engineers have anticipated the day when all trunk lines will be run with a standard gauge conductor, which will not be heavier than 50 lb. to the mile and will have an insulation resistance of 10 000 megohms per mile. A little later they hope to have one standard conductor for all subscribers and local junction circuits. They believe that it will be possible to telephone from any one point to any other in the United Kingdom and, further, that transcontinental and transoceanic telephony will soon be a reality. Already international telephony is a reality to some extent, but in the near future it is hoped to link up the trunk systems with the transcontinental and transoceanic cables. France, Italy, Japan, America and Germany are all using and experimenting with telephonic repeaters and have been so doing for some time, but the author has been informed that the British Post Office leads the field. The Post Office is greatly handicapped by a lack of sufficient research staff. The present staff is inadequate for the work that needs to be done, and the author believes that the Post Office is trying to extend the Research Department and that it intends to get into touch with our Universities in an endeavour to secure more men of the right sort who will keep us ahead in the struggle for efficiency and economy.

The author would like to express his indebtedness to Mr. J. Richardson, the Executive Engineer of the Birmingham Post Office, for much valuable information and advice and for permission to inspect the Birmingham repeater office. Lastly, he would like to thank Mr. E. T. G. Donovan, the Chairman of the Students' Section of the South Midland Centre, for his suggestion that a paper should be written on the subject of telephonic repeaters.

## APPENDIX.

In the preparation of the paper the author has consulted the following publications:

J. G. HILL: "The Loading of Aerial Lines, and their Electrical Constants," *Institution of Post Office Electrical Engineers, Professional Papers*, No. 54.

—— : "The Loading of Underground Telephone Cables for Phantom Working," *ibid.*, No. 68.

A. B. HART: "Telephonic Repeaters," *ibid.*, No. 75.

C. ROBINSON, B.A., and R. M. CHAMNEY, B.Sc.: "Gas-discharge Telephone Relays, and their application to Commercial Circuits," and "Technical Developments of Telephonic Repeaters since 1917," *ibid.*, No. 76.

All the diagrams in the present paper were reproduced from these papers.

# AUTOMATIC AND SEMI-AUTOMATIC RAILWAY SIGNALLING.

By H. S. Petch, B.Sc., Student.

(Abstract *of paper read before the* London Students' Section, *2nd December*, 1921.)

### Summary.

The evolution of railway signalling to meet the demands of safety, and later of traffic capacity, has culminated in the modern automatic and semi-automatic systems, which are designed to overcome the defects of manual working. In addition they offer valuable advantages, as their use permits of increased speeds and augmented services, which increase the full-load capacity of a given line; while their flexibility allows of a ready adjustment of traffic control to traffic variations.

An early system using train-controlled switches is briefly touched upon, and its weak points are noted.

The track circuit, which forms the basis of all modern automatic signalling, is considered in its simplest form, and also as modified to suit electrified lines.

Apparatus controlled by track circuits is described, together with additional schemes for its safe operation.

The functions and chief features of semi-automatic working are dealt with, and the advantages peculiar thereto are pointed out.

Finally, a description is given of some auxiliary apparatus designed to expedite the handling of traffic.

---

### Introduction.

The organized control of railway traffic came considerably later than the introduction of railways, and was first carried out solely on a time basis. Signals had no definite place in the regulation scheme, and were originally used for such purposes as stopping trains to pick up passengers. It was not until the danger of the time-spacing of trains was realized, and the block- or distance-spacing system was adopted, that signals achieved their present-day position as controllers of train movements.

At first scattered about as convenience or fancy dictated, the operating levers were finally centralized, and this, with the introduction of interlocking, formed the genesis of the signal box.

In 1889 the Board of Trade enforced the block-spacing system on all passenger lines, and so practically completed the development from the standpoint of safety. From that time onward the progress which has taken place has been towards a signalling system which, by its reliability and speed of operation, should allow of maximum traffic capacity. This has been accentuated by electrification, the full possibilities of which cannot be realized with the manual block system.

### Advantages of Automatic Signalling.

It is irrefutable that the manual block system, with its block indicators and complex bell signals, is entirely dependent for its safety on the human element and implicit obedience to rules. This may be quite satisfactory provided the density of traffic is not great, but it inevitably results in severe mental strain and consequent risks if the traffic density be at all high. Such achievements as 50 trains per hour are unattainable. The lock-and-block system, which relieves the signalman of a great deal of responsibility, is an advance, as trains are rendered in a large measure self-protecting; but full automatic working, which is the logical outcome of the lock-and-block system, appears to possess the following advantages over its prototype:—

(*a*) The elimination of the human element removes all danger of fatigue, renders the service less dependent on labour conditions and, by a psychological effect on the drivers, conduces to consistent high speeds.

(*b*) Speed may be maintained on the necessarily short sections found on city lines, the delays occasioned by telegraphing acceptance of trains being avoided.

(*c*) The flexibility of automatic working allows of an easy adjustment of the signalling system to deal with changes in traffic density. A few changes in wiring will achieve a result in an automatic system that would have necessitated, in a manual system, a new signal cabin and much fresh equipment.

### Lay-out of Signalling.

In a manual system a section is always treated as blocked unless specifically marked "clear" by the responsible signalman. The normal position of a manually operated signal is therefore at danger. An automatic signal is simply an indicator of the state of the section it controls, and its normal position is in consequence the "clear" position. It will be apparent that, with automatic working, trains may follow each other at an interval limited only by the time taken to traverse the longest section on the route, due regard being paid to time lost at junctions and in stations. The best lay-out of sections is therefore that in which trains traverse each section in equal times, and, as a change in load (i.e. passengers to be carried) will affect the time spent in station sections, it is obviously an advantage to be able easily to modify the signalling lay-out.

### Bar-and-treadle System.

The automatic system which perhaps follows most closely on the lines of manual working is the "bar-and-treadle" system. This system is now obsolete, but it deserves a brief description.

The equipment for each block section comprises a bar and a treadle, which are switches opened and closed respectively by the passage of a train over them; a relay; a source of electromotive force; and, of course, a signal. The power circuit of the signal is closed when the relay is operated, and the signal is thus held in the "clear" position.

When a section is clear, a circuit is closed from the battery, through the bar, a front contact of the relay (i.e. a contact closed when the relay is operated), and the relay coils. The relay is thus locked when operated, and the signal indicates "clear."

The entrance of a train into the section opens the bar, which is placed some 120 feet ahead of the signal, and the relay releases, as its holding circuit is broken. The signal power circuit is broken by the release of the relay, and, as the holding circuit of the latter is now open at the relay front contact, the closing of the bar after the train's passage does not again operate the relay. The signal therefore goes to "danger," and remains in that position while the section is occupied.

The train passes on, and in due course releases the signal of the next section at the next bar. Some 20 feet beyond the bar of the next section is the treadle of the first section. This is closed as soon as the train reaches it, and an operating circuit for the relay of the first section is then completed via the battery, the treadle, the bar of the next section at normal, the signal of the next section in the danger position, and the relay coils. The relay operates, and the front contact again completes the holding circuit, so that the signal of the first section is again held clear. The operating circuit of the relay is taken through the next signal so that the first section shall not be shown "clear" if the next signal has failed to go to "danger."

It is clearly important that only the passage of a train shall close the treadle. For this reason, treadles are usually operated by rail deflection, mercury often being employed to multiply the movement.

The bar-and-treadle system has the serious defect that the rear part of a train which has divided due to a broken coupling is not protected, as the front part will operate the treadle on leaving the section, so putting the controlling signal to "clear."

### THE TRACK CIRCUIT.

The track circuit, which is the basis of all modern automatic signalling, had an early origin, but was not brought into general use until recent times. It is called upon to function faultlessly under very severe conditions, and does so remarkably well. The fundamental principle involved is the continuous protection of an occupied section, as distinct from the "load and fire" action of the bar-and-treadle and kindred systems.

Fig. 1 shows the simplest possible direct-current track circuit. One of the running rails is bonded continuously along the line, while the other is divided by special insulated fish-plates into sections corresponding to the signal sections. The sectioned rail is also bonded between the section points. At the "exit" end of the section a source of electromotive force is connected across the rails through a fairly high resistance. At the "entrance" end a relay is bridged across the rails, and this relay controls the signal protecting the section. Any conductor of sufficiently low resistance will shunt the relay and release it if it is also bridged across the rails. There is a permanent shunt across the relay caused by the leakage path over sleepers and ballast, and the resistance of this leakage path varies from time to time from megohms to a few ohms, depending chiefly upon weather conditions.

Now, any given relay has definite operating and holding currents, and definite voltages must therefore be maintained at its terminals to operate it and to prevent it releasing. It will be apparent from Fig. 1 that, in a given set of conditions, there will be a certain value of the ballast leakage resistance which will prevent the relay operating with a clear track. This may be called the "ballast failing resistance" and, clearly, the particular value which will produce failure in a given case is controlled by the value of the series resistance. The particular ballast failing point for which the series resistance is set is a matter of great importance. It must not be made higher than the normal resistance of the ballast leakage path, or continual failures would result in damp weather. On the other hand, it must be kept as high as possible, as upon it depends the capability of the track circuit to deal with train shunts of high resistance. A remedy for track circuits which, by reason of their excessive length or damp situation, necessitate the adoption of an unreasonably low ballast failing point, consists in splitting the section into several track circuits each of which exerts control on the signal.

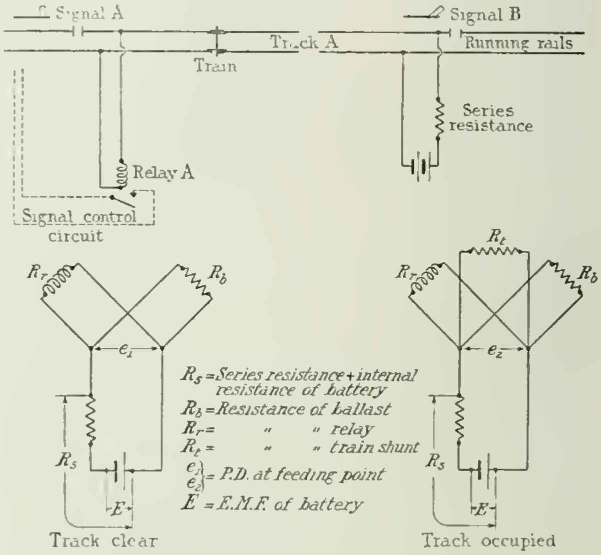


FIG. 1.—Simple d.c. track circuit.

The resistance of the shunt introduced by the presence of a train in a section must so reduce the combined resistance in series with the feeding resistance that the potential difference across the rails falls below that necessary to hold the relay in operation. For a given track there is thus a maximum effective train shunt resistance, and this will clearly have its smallest value when the ballast leakage resistance is infinite. It is important that a track circuit shall have the highest possible effective train shunt resistance, as train shunts, in common with ballast leakage, are very variable, being affected by the weight of the trains and the state of the contact between wheels and rails.

The connection between the ballast failing point and the maximum effective train shunt can be shown mathematically.

Let $E$ = E.M.F. of battery,
$e$ = potential difference at the feeding point,
$e_o$ = operating voltage of relay,
$e_h$ = holding voltage of relay,
$e_m$ = maximum potential difference across rails,
$k$ = ratio $e_o/e_h$,
$R_s$ = series resistance (including battery),
$R_r$ = resistance of relay,
$R_b$ = resistance of ballast leakage path,
$R_t$ = resistance of train shunt,
$R_{b'}$ = ballast failing resistance,
$R_{t'}$ = maximum effective train shunt.

(*Note*.—Rail resistance is negligible if the bonding is well carried out.)

A general expression for $e$ is :—

$$e = \frac{E}{1 + R_s[(1/R_r) + (1/R_b) + (1/R_t)]} \quad . \quad (1)$$

The value of $R_s$ must satisfy the following equation :—

$$e_o = \frac{E}{1 + R_s[(1/R_r) + (1/R_{b'})]} \quad . \quad . \quad . \quad (2)$$

whence

$$R_s = \frac{E - e_o}{e_o[(1/R_r) + (1/R_{b'})]} \quad . \quad . \quad . \quad (3)$$

From Equation (1) it will be apparent that the maximum rail potential $e_m$ will occur when $R_b$ and $R_t$ are both infinite, and will then be :—

$$e_m = \frac{E}{1 + R_s(1/R_r)} \quad . \quad . \quad . \quad . \quad (4)$$

$$= \frac{ER_r}{R_r + R_s} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Now, the maximum effective train shunt $R_{t'}$ will be that resistance which will reduce the track potential from its maximum value $e_m$ to the holding P.D. of the relay, $e_h$, and so just release the relay. This can be shown to be given by the equation

$$R_{t'} = \frac{R_s}{E[(1/e_h) - (1/e_m)]} \quad . \quad . \quad . \quad (6)$$

For a given relay, the ratio $e_o/e_h (= k)$ is fixed, and substituting $k$ for this in Equation (6), together with the previously found values for $e_o$, $e_m$ and $R_s$, the final expression for $R_{t'}$ is :—

$$R_{t'} = \frac{(kE - e_h)R_rR_{b'}}{(1 - k)ER_{b'} + R_r(E - e_h)} \quad . \quad . \quad (7)$$

Since $E$, $e_h$ and $R_r$ will have fixed values for a given track circuit, it is clear that $R_{t'}$ will be equal to $R_{b'}$ when $k$ is unity (i.e. when the operating and holding voltages of the relay are identical), and that it will be less than $R_{b'}$ for all values of $k$ below unity. Thus under the worst conditions the maximum effective train shunt will be somewhat less than the ballast failing resistance. This demonstrates the importance of adjusting a track to the highest possible ballast failing point, and also the desirability of using a relay the operating and holding currents of which are as nearly equal as possible.

### Direct-current Track Circuits for Electric Railways.

While the simple track circuit is quite suitable for use on steam railways, the proximity of the conductor rails on electric lines introduces the probability of considerable leakage currents from the traction power circuits. Such leakage currents could easily produce a dangerous failure on a simple track circuit, and therefore special circuits have been devised to meet this difficulty. One such scheme, the invention of Mr. H. G. Brown, employs a pair of polarized relays, one at either end of the track circuit, and both of these must be operated before the protecting signal can go "clear." The relays are operated by current in the proper direction only, and any fault or leakage current which may cause one to operate will flow in the opposite direction in the other and so prevent its operation. To secure economy of power, the polarizing coils of these relays are closed by a pilot armature which is attracted only when sufficient current flows in the main coils, which are bridged across the rails as before.

### The Alternating-current Track Circuit.

This is now generally conceded to be the most economical and reliable form of track circuit for electric railways. The following are some of the advantages which it possesses :—

(*a*) Alternating-current apparatus is unaffected—except by magnetic saturation and overheating—by direct-current leakage currents.
(*b*) Economy in wiring is obtained, due to the ease of transformation to the low voltages necessary for track circuits.
(*c*) A given track circuit will have a higher maximum effective train shunt as, in addition to the utilization of current-changes, an alternating-current circuit also employs changes of phase angle.

Alternating-current track circuits are fed at the exit end from the low-voltage secondaries of the feeding transformers through regulating resistances. These transformers, which are individual to the tracks, are fed from main transformers, the primaries of which are connected to the signal mains. The relays used are usually of the two-winding type. The field windings are continuously excited, and the armature windings bridge the rails. The relays are ironless, to minimize power consumption, and function as dynamometers. An induction-type relay is sometimes used, but its working force is smaller than for the two-winding type.

Fig. 2 shows a typical a.c. track circuit scheme embodying the above features and utilizing impedance bonding, which allows of the use of the running rails as regular returns for traction current, at the same time preserving the independence of the track circuits.

A theoretical discussion of the a.c. track circuit is beyond the scope of this paper, but in 1920 a comprehensive paper on the subject appeared in the *Journal*.*

### CONTROL OF APPARATUS BY TRACK CIRCUITS.

Both electric and pneumatic drive are used for signals and points, but on an electric line the flexibility of the electric drive makes it by far the more suitable. In the all-electric system, the circuits controlling the various pieces of apparatus are usually made and broken directly by the track-circuit relays. In the electro-pneumatic system the track relays control solenoid-operated valves, which in turn control the admission and release of compressed air to the operating cylinders of the apparatus concerned. In both systems the control circuits are usually fed from the same mains that feed the track circuits.

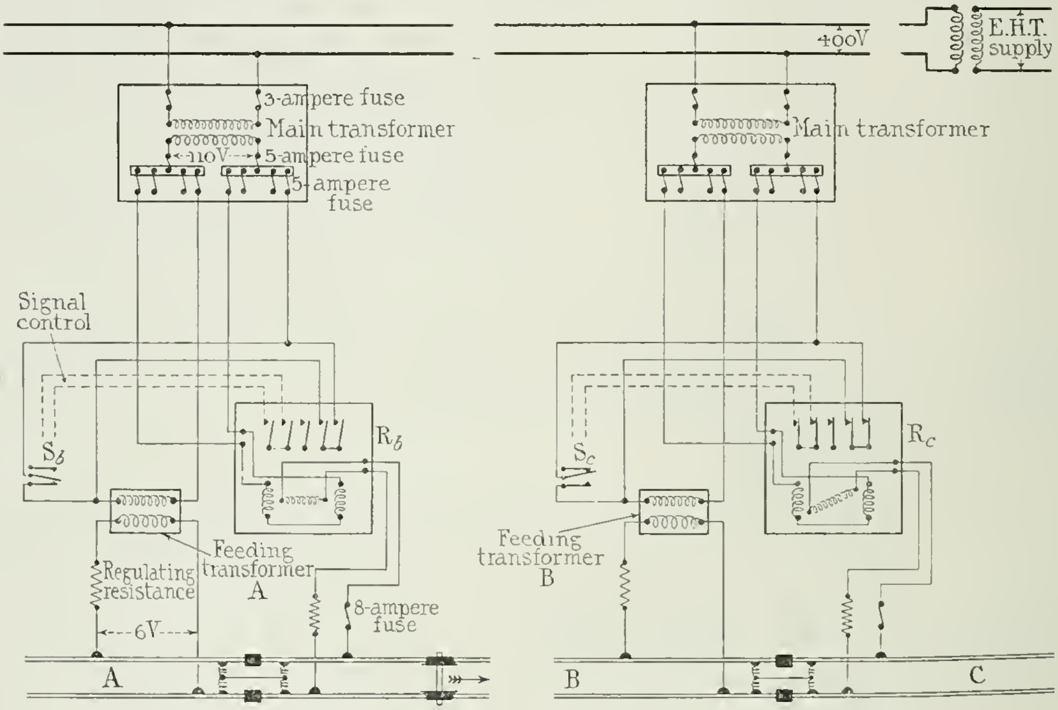


FIG. 2.—Alternating-current track circuit.

### SIGNALS AND "SIGNAL-ON" PROTECTION.

The simplest signals are those used in tunnels, and of these there are two general types. The first employs separate lamps and lenses for the red and green indications. The other uses one lamp only with an interposed spectacle frame, which puts a green glass in front of the lamp when raised by a solenoid, and a red glass when the de-energized solenoid allows the spectacle to fall.

In the two-lamp type the lamps are in a separate ventilated chamber, and are controlled by a relay enclosed in the signal. The red-lamp circuit is a local one, to reduce to a minimum the chances of its failure. The green lamp and the signal relay coils are energized through track relay contacts so that the green lamp will be extinguished by the release of the track relay in the event of the signal relay sticking up. The signal relay carries contacts to control repeater signals, and also the signal-on contacts.

The object of "signal-on" protection is to prevent the marking "clear" of a section if for any reason the signal of the section ahead has failed to go to "danger" behind a train. In Fig. 2 it will be seen that the circuit of the feeding transformer of section B passes through the back contacts of signal C($S_c$) and front contacts of relay C($R_c$) in parallel. Thus, assuming a train to have entered section C and to have released $R_c$, and that for some reason $S_c$ fails to release, the feed to track B will be broken. Consequently, although track B may be unoccupied, $R_b$ is prevented from operating and putting $S_b$ "clear" until the feed to track B is restored either by the release of $S_c$ or by the subsequent operation of $R_c$ when the train leaves section C. It will be seen that this is equivalent to controlling a signal from two track circuits in the event of the second track failing to release its own signal.

On lines which run in the open, semaphore signals are used. In the upper-quadrant pattern the arm is raised through 45° by a motor which drives through a magnetic clutch. Both motor and clutch are energized through the track relays, and, when the arm has been raised sufficiently, the motor is cut out, leaving the arm held "clear" by the clutch. On the release of the track relays the clutch circuit is broken, so that the arm falls to "danger" by gravity, the shock being taken up by an air-cushion.

---

* *Journal I.E.E.*, 1920, vol. 58, p. 491.

### Functions of Semi-automatic Signalling.

The systems of signalling so far dealt with have been suitable for sections having only one entrance and one exit. Sections involving choice of route, or where shunting operations take place, call for a certain amount of manual control. Semi-automatic signalling is designed to reduce this necessary manual control to a minimum, and so to retain the advantages of full automatic working as far as it is practicable. A signalman is necessary at a junction in order to switch trains to their correct routes, and also to decide as to priority when two trains converge toward the same road. By limiting his responsibility to these duties, and providing him with suitable apparatus, the traffic-handling capacity of a signalman can be increased to a very great extent.

### Leading Features of Semi-automatic Systems.

(*a*) *Power control.*—The control of points and signals by power instead of by rods and wires reduces the signalman's work, and also renders the incorporation of special schemes of protection an easy matter. The levers in a power signal frame operate switch-drums, and are mechanically interlocked among themselves to prevent conflicting train movements. Thus, the lever of a signal which gives access to points cannot be pulled over unless the point lever concerned is in the correct position. Further, the pulling over of such a signal lever back-locks the point lever, to prevent the movement of the points during a train's passage. Again, the pulling of a point lever to set the road through a crossing prevents the pulling of the lever which would set the intersecting road. The switch-drums operated by the levers serve, of course, to control the circuits of the various points and signals.

(*b*) *Illuminated diagram.*—Above the lever frame in a semi-automatic signal cabin is mounted a diagram of the area of control. The diagram is set out on glass, and the various roads are frosted. The roads are divided to correspond to the track circuits, and each division is normally illuminated by a lamp behind the glass. The lamp circuits are controlled by line relays which serve to repeat the condition of the track circuit relays, and the fact that a particular track is clear or occupied is therefore shown on the diagram by the corresponding section being illuminated or darkened, respectively. Train movements are thus revealed in the cabin by the progress of dark sections along the otherwise illuminated tracks. In addition to the track circuit lamps, small red lamps are placed on the diagram in positions corresponding to the signals, and these are extinguished when the signals are "clear." As these lamps are controlled by the signal relays they serve as checks on the signal operation.

It is usual to indicate on the diagram one or two of the automatic track circuits on each line of approach to the junction, so that the signalman may have warning of oncoming trains.

The use of such an illuminated diagram allows the signalman to concentrate his whole attention on the lever frame; permits the placing of the signal cabin out of sight of the trains altogether; and prevents the working of the junction being interfered with by fog.

(*c*) *Control of points.*—In a power frame, a switch-drum which controls points has four positions. The point lever is capable of moving it to only one of the two inner positions, and in these positions, as shown in Fig. 3, the circuit of the point motor alone is completed. When power is thus applied to the motor, the bolt of the points is first withdrawn, then the blades are thrown over and, finally, the bolt is re-inserted. Power is cut off from the motor at the end of a stroke by a switch-barrel in the detection box, which switch-barrel is associated with, and controlled by, the bolt.

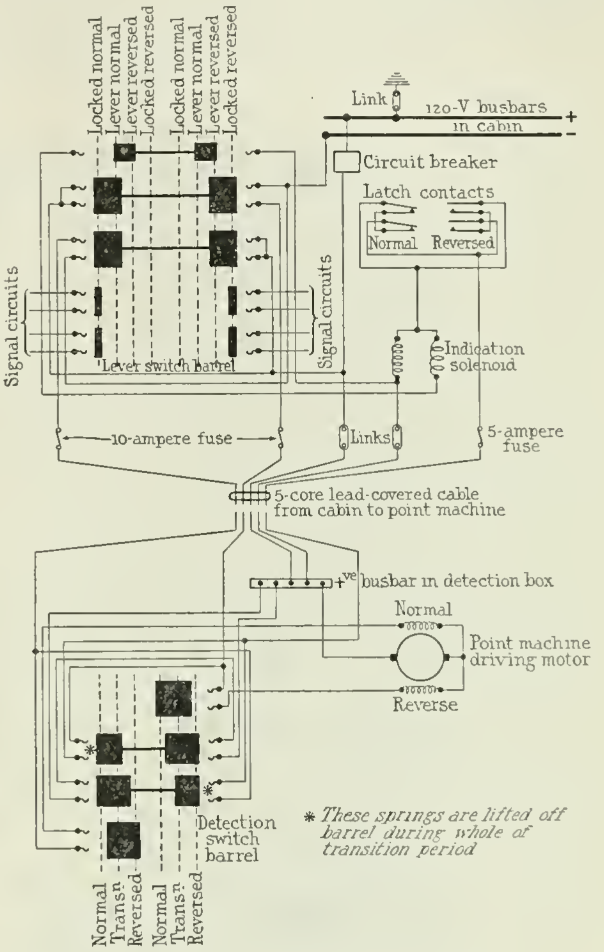


Fig. 3.—Circuit of power-operated points.

The detection switch-barrel is also responsible for the completion of the circuit of the indication solenoid which, when it operates, moves the lever switch-drum to one of its extreme positions. The contact fingers in the indication circuit are lifted clear of the detection switch-barrel by an auxiliary device if the point blades are not fully thrown, so that the fact that the lever switch-drum is in either extreme position is a guarantee that the points are safe for traffic.

It will be observed from Fig. 3 that the indication circuit is taken through contacts operated by the lever latch, the lifting out of which opens the indication circuit, and so causes the lever switch-drum to leave its extreme position. It will also be noted that the indication solenoid has a low-resistance operating coil, and a high-resistance holding coil, the object of which is economy of power.

(*d*) *Control of signals.*—The signals used for semi-automatic working are identical with those previously described—but in this case they must normally stand at "danger." Signal lever switch-drums in a power frame are coupled direct to their levers, so that the point levers, via the mechanical interlocking, prevent the closing of conflicting signal control circuits by locking the levers. Fig. 4 gives the signal control circuits of the junction shown on the diagram and shows that the control circuit of any particular signal passes through contacts on the switch-drums of any points to which the signal gives access. (For example, the circuit of signal S1 cannot be closed unless points P3 and P4 are normal and reversed, respectively.) As these contacts on the point lever drums are closed only in the extreme positions of the latter (see Fig. 3), it follows that not only must the point levers be thrown, but the points themselves must be safe for traffic before the signal circuit is closed. Finally, it will be seen that the control circuit of a signal passes through contacts on the line relays associated with the track circuits to which it gives access. Thus, a signal cannot be put to "clear" unless the section to which it admits is unoccupied, and, although put "clear" manually, a signal will go to "danger" automatically on the entrance of the train into the section.

In order to permit the passage of a train, the signalman will first set the road by the point levers, and immediately throw the appropriate signal levers. The signals, however, will respond only when all the above conditions are fulfilled.

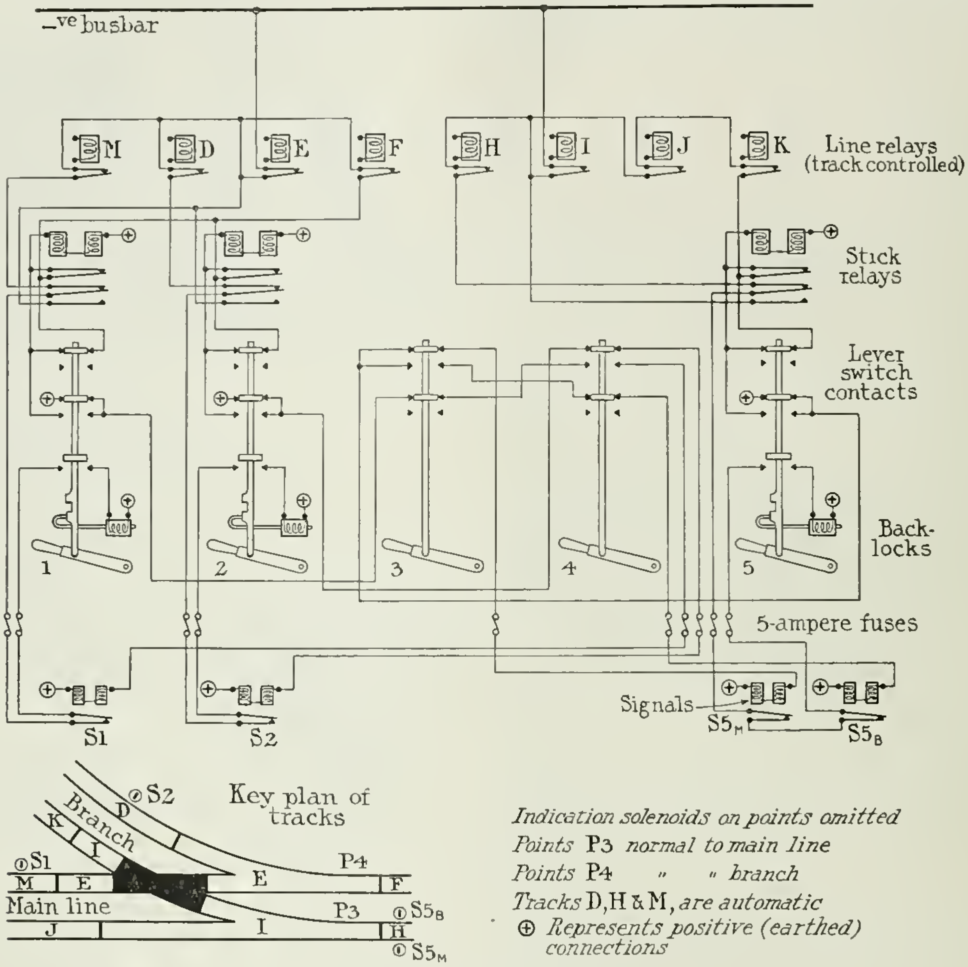


FIG. 4.—Signal circuits at a junction.

Fig. 4 also shows the ease with which one lever can be made to operate two signals. Thus, signals $S5_M$ and $S5_B$ are both controlled by lever 5, the selection being dependent on the position of the points P3.

(*e*) *Electric route-locking.*—It is essential for safety that once a train has been admitted to a section containing points it shall not be possible to disturb the setting of the road until the section is clear again. This is accomplished in a semi-automatic installation by back-locking the signal levers electrically. Suppose, for example, a train to be approaching the junction in Fig. 4 along track M. The signalman will set the road for it by reversing points P4. He will then throw lever 1, which will mechanically lock and back-lock points P3 and P4, respectively, and put signal S1 to "clear" if the road is clear and the points are safe. As soon as lever 1 is thrown, however, the back-lock latch will drop into a slot in the switch-drum, and this will prevent the replacement of lever 1 and the consequent freeing of the mechanical locking of points P3 and P4, as the circuit of the back-lock release solenoid will be open at signal S1, and at line relay M, which will be released by the presence of the train in track M. The route for the train is thus guarded, and the train may proceed along it.

As soon as it enters track E, line relay E will release, thereby opening the circuit of signal S1 (which will go to "danger") and also releasing stick relay No. 1. The stick relay is so called because it has a locking action, and, when it is released, the back-lock release circuit of lever 1 will no longer be under the control of line relay M, so that the clearing of track M when the train leaves it will not free the back-lock.

The train may thus traverse the junction track E in perfect safety, as the road cannot possibly be interfered with. In due course the train will enter track F, releasing line relay F. This makes a further break in the circuits of signal S1 and stick relay No. 1, and ensures that neither shall again operate until the train has left the section, which in this case comprises tracks E and F.

Now when the train has left track E there is no reason for maintaining the lock on points P4 and P3, and their release will enable the signalman to prepare the road for other trains. Accordingly, the operation of line relay E completes the back-lock release circuit of lever 1 through a contact previously closed by the release of stick relay No. 1. Lever 1 may then be replaced, thus freeing the mechanical locking of points P3 and P4.

When the train leaves track F, and so passes beyond the control of signal S1, line relay F will operate, closing the operating circuit of stick relay No. 1 if lever 1 has been replaced, or putting signal S1 to clear if the lever is left thrown. The operation of the stick relay closes the locking circuit for itself, and also restores the control of the back-lock on lever 1 to track M.

It will be apparent that by leaving lever 1 thrown, trains may be worked automatically through the junction from track M. This also applies to the other levers, and is a very valuable feature, as, by pulling the necessary levers for through traffic, a signal cabin may be left unattended except when switching or shunting operations are to take place.

The back-locks on the signal levers are so arranged that the levers may be replaced far enough to throw the signals to "danger" at any time, but can only be completely replaced and so free the mechanical locking of the points when this is safe. To economize in power, the back-lock circuits are taken through contacts on the switch-drums of their respective levers, and these contacts are closed during the mid-stroke only.

To overcome the difficulty introduced by the possibility of a signalman lowering the wrong signal in front of a train which approaches on a facing road, a sealed release key is provided in the back-lock circuits of such signals. The use of this key is rightly regarded as a serious matter, and has to be reported immediately.

Electric route-locking, combined with the continuous detection of signals through the points, obviates the necessity for facing-point locking bars and is especially valuable in more complex junctions where one signal may admit a train to several sets of points, as it combines complete safety with a minimum of lost time, since the locking is removed as soon as this is allowable.

### AUXILIARY APPARATUS.

(*a*) *Route indicators.*—These are used at complex junctions to avoid a large number of levers in the signal frame. For example, a single signal lever and signal may admit trains to any of a number of platforms, the drivers being apprised of the route by the exhibition of an illuminated number below the signal. The various indicator circuits are detected through all the points on the respective routes to which they give access, and each route electrically back-locks the signal with which the indicator is associated.

(*b*) *Magazine train describer.*—A train describer is an aid to the expeditious working of junctions, as it shows in a signal cabin the destinations of all trains approaching on facing roads, so that the signalman may set the road correctly without it being necessary for him to observe code headlights.

Either at the previous signal cabin or at the previous station, there is a multiple-way switch, which is set by hand to correspond to the destination of each train as it passes. An illuminated indicator shows the driver if the description is correct, and, after passing the indicator, the train operates a special treadle. This treadle energizes a set of solenoids in the signal cabin, according to some particular combination determined by the position of the multiple-way switch at the previous cabin. These solenoids, when operated, push in pegs in the periphery of a drum, which rotates one step as each train is described. A set of contact fingers inside the drum, which rotate with it as the trains are described, rest on those pegs in a row which have been pressed in, and so complete circuits which cause an indicator above the lever frame to take up a position which gives the required description. As each train enters the junction track circuit another solenoid is operated, and this causes the contacts inside the drum to move back one step relative to the drum, thus cancelling the description, and setting up that of the next train, the cancelled pegs then being restored to normal. The device can thus store up the description of several trains, and will give them out as required. This train describer can be used to operate destination indicators on each station, thus adding to the convenience of passengers, and tending to reduce platform time.

(*c*) *Train-stops.*—Train-stops are fairly well-known pieces of apparatus, and can be used in conjunction with signals of all types. When a signal is at danger, its associated train-stop raises a small arm just above the rail level, which will trip a valve on the brake pipe of a train attempting to pass the signal, and so arrest its progress. The train stops are usually wired in parallel with their associated signals.

(*d*) *Repeaters and fog repeaters.*—Repeater signals are installed where the view of the line ahead is poor, or where fast trains are run. They are distinguished from stop signals by a different colour scheme, and are usually controlled by contacts on the relay of the stop signal which they repeat. Where a repeater of the stop signal ahead is mounted on the same post as a stop signal, both stop signals control the repeater to prevent the anomaly of a repeater at "clear," and a stop signal at "danger," on the same post.

Fog repeaters were introduced by the Metropolitan Railway as an improved means of combating the effects of fog. They are placed on a level with the drivers' eyes, as near to the track as possible, and sufficiently far in advance of the stop signals which they repeat to allow drivers to pull up before reaching the stop signals. A fog repeater consists merely of a pair of lamps and lenses, and the lamp circuits are controlled in parallel with the lamps of the associated stop signal. The repeater lamps are also controlled by a switch placed at the nearest signal cabin or station, and can therefore be switched on as soon as a fog occurs, thus avoiding the delay occasioned by the calling out of fogmen.

### THE EFFECT OF FAULTS.

In signalling work it is essential that faults shall never produce a false "clear" indication. Accordingly, the circuits are arranged so that the wiring must be intact, and the power must be on in order to hold a signal at "clear." Where any discriminatory action is effected by switch-drums, the possibility of circuits on both sides being simultaneously energized is guarded against by such an eventuality producing a short-circuit.

### POWER SUPPLY AND CONSUMPTION.

On electric lines, power for signalling is usually derived from the extra-high-tension mains through transformers and/or motor-generators set apart for the purpose. For isolated installations batteries are employed, and can be conveniently housed beneath the signal cabin.

Power signalling is quite economical, as 0·3 kW per mile of single track is usually sufficient.

# THE IMPROVEMENT OF POWER FACTOR.

By the late* Dr. GISBERT KAPP, Past President.

(*Paper first received 4th April, and in final form, revised by* Prof. MILES WALKER, *24th October,* 1922; *read before* THE INSTITUTION *16th November, before the* NORTH-EASTERN CENTRE *13th November, before the* NORTH MIDLAND CENTRE *21st November, before the* LIVERPOOL SUB-CENTRE *27th November, before the* NORTH-WESTERN CENTRE *28th November, and before the* WESTERN CENTRE *4th December,* 1922.)

SUMMARY.

The economical limit of power factor improvement in relation to capital outlay. It is shown that if $C$ is the capital cost of generating and transmission plant per kilowatt, and $c$ is the cost of phase-improving plant per wattless kilovolt-ampere; then, writing $a = c/C$, it is economical (from the capital outlay point of view) to go on improving the power factor until $\sin \phi = a$, where $\phi$ is the angle of lag. The saving thereby effected is equal to $100[1 - \cos(\phi_0 - \phi)]$ per cent, where $\cos \phi_0$ is the original power factor before improvement. A practical example is worked out to show the operation of this rule. The synchronous motor and static condenser serving exclusively for injecting leading kVA are considered. The rotary converter and the synchronous induction motor serving the double purpose of supplying power and injecting leading kVA are dealt with and their province is described. Various methods of starting the synchronous induction motor are illustrated. The paper then goes on to treat of phase advancers of the rotating type connected to the slip-rings of induction motors. The effect of such advancers upon the performance of the induction motor is illustrated by several examples, and the change in the shape of the circle diagram is worked out. The author then proceeds to give an expression for the apparent capacity of his "vibrator" in terms of the constants of the machine, and shows how to arrive at the size of vibrator required to suit any given conditions. The last section of the paper deals with meters and tariffs. Various methods of indicating kW maximum demand and wattless kVA are described and particulars are given of the tariffs employed by various power companies. Observations are made as to the fairness of these to consumers who improve their power factor.

This paper deals with the use of such consuming devices, or the addition to existing consuming devices of such apparatus, as will diminish the phase angle between the vectors representing electromotive force and current. As in the majority of cases the current lags, the improvement in the power factor consists of the pushing forward of the current vector in the direction in which the vectors are rotating; but this is not necessarily always so. With the modern development of long-distance transmission, cases may arise where the current naturally leads, and then we want appliances not to advance it still further, but to retard it.

The primary object of power factor improvement is the better utilization of the electrical plant and, as far as the supply company is concerned, this includes the generator, step-up and step-down transformers, feeders, mains and switchgear up to the consumer's terminals. Whether the consumer's individual motors have a good power factor does not directly concern the supplier; all he asks is that the consumer shall take from his terminals a current nearly in phase with the voltage. This condition the consumer can always fulfil, either by employing good-power-factor motors, or by improving his plant by the addition of apparatus which will inject leading kVA into his terminals so as to bring up the general power factor of his installation to a reasonably good figure. That all consumers on a system should voluntarily incur the expense involved cannot be expected. The supplier must therefore make it worth their while, and thus the purely technical question of power factor improvement becomes tied up with the question of suitable tariffs.

This does not, however, exhaust the subject. Even assuming that the supplier were by a suitable tariff able to induce all his consumers to improve the peak-load power factor to unity, he would still have to face the question of his own power factor, not so much on account of the better utilization of the electrical plant as on account of his being under the obligation of supplying current at a stated voltage. In a small system with only a moderate diversity in the load characteristic between the consumers no difficulty arises, but in an extended system with long feeders the combined effect of reactance, resistance and capacity may be different on every feeder, and this effect will generally tend to make a difference of phase between current and voltage. Therefore, correcting devices should be used at the feeder ends. If the load on any particular feeder should be very light a device injecting permanently a given amount of leading kVA would cause the voltage to rise, and that is inadmissible; hence the necessity of an adjustable device such as an idle-running synchronous alternator. Examples will be given later.

## APPARATUS USED FOR POWER FACTOR IMPROVEMENT.

The various appliances may be classified as follows:—

(*a*) Apparatus serving exclusively for injecting leading kVA at the end of a feeder, or at the consumer's terminals, for the purpose of improving the power factor of the system as a whole without affecting that of individual consuming devices. To this class belong the static condenser and the idle-running synchronous machine also known under the names dynamic condenser, rotary condenser, or synchronous condenser.

(*b*) The over-excited synchronous motor serving for the double purpose of producing motive power and injecting leading kVA into the system, and thus making up to a certain extent for lagging kVA taken by other consuming devices on the same system. To this class belongs also the a.c. to d.c. converter used in traction stations, the synchronous motor-generator, and the synchronous induction motor.

(*c*) The rotary or oscillating phase advancer acting on the slip-ring current of a motor so as to improve the power factor of this individual motor and, incidentally, also increase its overload capacity.

---

* Dr. Kapp died on 10th August, 1922.

(*d*) The a.c. commutator machine or rotary phase advancer applied to the slip-rings of the motor and serving the double purpose of improving the power factor and acting as a slip regulator.

These various classes are considered further on, but before entering into questions of detail it is expedient to consider:

## THE ECONOMICAL LIMIT TO POWER FACTOR IMPROVEMENT IN RELATION TO CAPITAL OUTLAY.

The introduction of any kind of power factor improver to existing motors or other consuming devices necessarily involves some capital expenditure, but at the same time it reduces the capital cost of the electrical part of the generating and transmitting plant. Where, as in a private works, the supplier is also the consumer, the relation between extra expense on the consuming plant and saving of expense on the supply plant is direct and obvious. In the case of a supply company and its many consumers this relation may at first sight not be so obvious, nor so simple, because many non-technical considerations enter into the commercial business of buying and selling. Nevertheless, the relation exists. If the customer cannot participate to a reasonable extent in the benefit he confers by installing plant of good power factor, he will naturally refrain from doing so. On the other hand, if the customer demanded so large a reduction in tariff as to swallow up all the benefit, the company would naturally refuse to give that reduction and there would again be no phase-advancing, to the detriment of both parties. Thus the problem of the economic limit of power factor improvement is largely dependent on the cost of suitable apparatus, on the one hand, and the saving effected in the cost of saleable or available kW on the other.

When treating the question on broad lines and mathematically, we are therefore justified in taking the case of a private works, and we are indeed compelled to do so, because no mathematical formula can take account of the many side issues that may be raised between supplier and consumer which, even if not preponderant, must obscure the mathematical reasoning.

Let us then assume that a private works with a prospective peak load of 1 000 kW is to be established. The load may be provided for without the assistance of any provision for power factor improvement, and its cost will then be a maximum because the electrical part of the generating and transmitting plant is proportional to the kVA (not the kW) demand; or power-factor-improving apparatus may be used, in which case the generating and transmitting plant will be cheaper, but the consuming plant will cost more. The question is: How far should power factor improvement be carried so that the total cost becomes a minimum? The influence of power factor on the capital outlay for the prime mover is only indirect and is generally small, though it may be considerable with regard to working expenses. As we are now dealing only with capital outlay we disregard this part of the problem.

Let $C$ = cost of generating and transmission plant per kW from the alternator to the points of supply at unity power factor.

$\phi_0$ be the angle of phase difference between the current and voltage vectors when no phase-improving apparatus is used.*

$\frac{C}{\cos \phi_0}$ = corresponding cost per kW at a power factor of $\cos \phi_0$.

$c$ = cost of phase-improving plant per wattless kVA injected into the supply terminals.

$a = \frac{c}{C}$

$\cos \phi$ = most economical power factor to which the whole system can be brought.

Both $\cos \phi_0$ and $\cos \phi$ are for peak load, not average power factors.

The total cost (excluding consuming devices) of the electrical plant is, per kW:

$\frac{C}{\cos \phi_0}$ . . . without power factor improvement.

$\frac{C}{\cos \phi} + aC (\tan \phi_0 - \tan \phi)$ with power factor improvement.

This becomes a minimum for

$$\sin \phi = a$$

and the total cost for a peak load of $P$ kW is

$$PC[\sqrt{(1 - a^2)} + a \tan \phi_0]$$

instead of $PC/\cos \phi_0$ without power factor improvement.

The peak-load power factor to which the installation as a whole should be improved is

$$\cos \phi = \sqrt{(1 - a^2)} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and the saving thereby effected is

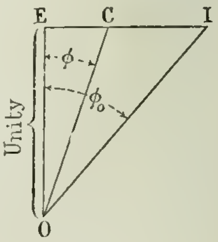
$$100[1 - \cos (\phi_0 - \phi)]$$

per cent of the outlay for generating and transmitting plant without power factor improvement.

It will be seen from Equation (1) that the economical limit of power factor improvement does not depend on the power factor of the unimproved plant, but only on the ratio of the cost per kW of the original plant at unity power factor to the cost per wattless kVA injected by the phase advancer.

---

* The relations between the various quantities considered in this paragraph are apparent from the attached figure. If OE is taken as the direction of voltage vector, OI is the direction of the current vector before power factor improvement, and OC the direction of the current vector after power factor improvement. If OE is taken as unity and represents to scale the current required for one kilowatt at unity power factor, then $OI = 1/\cos \phi_0$; $EI = \tan \phi_0$ = wattless current per kW delivered before improvement; $EC = \tan \phi$ = wattless current per kW after improvement. Then $(\tan \phi_0 - \tan \phi)$ represents the wattless current supplied by the power-factor-improving apparatus.—M. W.



The relation between $\alpha$ and $\cos\phi$ is simply that of a circle function, thus:

$$\begin{array}{rccccc} \alpha = & 0{\cdot}1 & 0{\cdot}2 & 0{\cdot}3 & 0{\cdot}4 & 0{\cdot}5 \\ \cos\phi = & 0{\cdot}995 & 0{\cdot}98 & 0{\cdot}955 & 0{\cdot}915 & 0{\cdot}865 \end{array}$$

Since $\alpha$ is generally very small (say within the limits 0·1 and 0·3) power factor improvement may economically be carried fairly near to unity power factor, but should not be carried beyond it so as to make $\phi$ negative. This refers to the installation as a whole, but does not mean that any individual motor may not be worked with a leading power factor if thereby the overall power factor can be brought up to the economic limit

From the above mathematical arguments we can deduce a few simple relations as to the cost of power factor improvement if done in the most economical manner as regards capital outlay.

Let $K$ be the cost of the original plant without any improvement; $K_1$ the cost of the reduced generating and transmitting plant when a phase advancer is added; and $A$ the cost of the phase-advancing plant itself. Let $S$ be the saving in capital outlay through using phase advancers. Then the following relations obtain:

$$S = K - K_1 - A$$

$$K_1 = K\frac{\cos\phi_0}{\cos\phi}$$

$$A = K\alpha\cos\phi_0\,(\tan\phi_0 - \tan\phi)$$

$$\frac{A}{K_1} = \alpha\cos\phi\,(\tan\phi_0 - \tan\phi)$$

$$\frac{S}{K} = 1 - \cos(\phi - \phi_0) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The following table shows the saving in capital outlay effected by power factor improvement for a few values of $\alpha$ and $\cos\phi_0$.

| $\cos\phi_0$ . . | 0·6 | | | 0·7 | | | 0·8 | | |
|---|---|---|---|---|---|---|---|---|---|
| $\alpha$ . . . . | 0·1 | 0·2 | 0·3 | 0·1 | 0·2 | 0·3 | 0·1 | 0·2 | 0·3 |
| $S/K$ in per cent | 32 | 24 | 18 | 22 | 16 | 11 | 14 | 9 | 5 |

To form an opinion as to whether such a saving in initial cost of a private works for 1 000 kW peak load to be newly established is of importance, we may, by way of example, assume likely values for $\cos\phi_0$, $C$ and $\alpha$. A fair value for the peak-load power factor is 0·75. This might perhaps seem too low to some, but we must remember that not all the motors will be large or fully loaded even at peak time. There may be a number of small motors and these, or many of them, will generally be underloaded. Very often this is also the case with large motors. As a rule, consumers buy their motors rather too large because they want a good margin in torque in the case of short-time or sudden overloads. Hence the high full-load power factors which we find in motor lists cannot be expected under average running conditions. The installation may also contain some consuming devices (arc lamps or electric furnaces) with a bad power factor, so that in assuming the overall peak-load power factor to be 0·75 we shall not be far wrong. The estimate of the quantity $C$ is much more uncertain. $C$ includes cost of generators, connections to switchboard, all the switchgear, step-up transformers, protection devices, feeders, step-down transformers, some switchgear at the feeder terminals, and some mains up to the terminals to which the consuming devices are connected. Possibly transformers may be omitted, but heavier feeders will then be required, so that this item cannot make much difference in the total. The influence of size and speed of the generating units is more important; but here also the margin is not very large. It would hardly be safe to put down less than three units of 500 kW each so as to have one spare. If the process of working involved long spells of light load, bringing the conditions of working nearer to those obtaining in a large power station for general supply, four units might be even better because this would reduce working expenses. Another factor of uncertainty is the cost of the line, whether overhead or cable. It is obviously impossible to adopt a definite value of $C$ fitting all cases, nor is it necessary, because from their own experience members can adopt the value which fits an actual case and can repeat the calculation here given merely by way of example. For the purposes of this example we may take $C = 12$, which means that the cost of the plant working at unity power factor comes to £12 per kW. The cost of power-factor-improving plant per kVA varies within wide limits; it may be as low as 10s. with a phase advancer applied to the slip-rings of a very large induction motor, or it may go up to £4 or £5 with static condensers. In order not to overstate the argument for phase-advancing, the cost is here taken at £3. This makes $\alpha = 0{\cdot}25$. We thus find $\cos\phi = \sqrt{(1 - 0{\cdot}0625)}$, or

$$\cos\phi = 0{\cdot}965\,;\ \phi = 14^\circ\ 30'\,;\ \phi_0 = 41^\circ\ 25'\,;$$
$$\phi_0 - \phi = 26^\circ\ 55'\,;\ \cos(\phi - \phi_0) = 0{\cdot}89.$$

Saving = 100 − 89 = 11 per cent.

The installation for the 1 000 kW peak load would cost $\frac{12}{0{\cdot}75} = £16$ per kW, or £16 000 in all for the electrical plant; but by adopting phase-advancing we improve the overall power factor to 0·965 and reduce the total cost to 16 000 minus 11 per cent of 16 000 = £14 240. Of this sum, about £12 500 is required for generating and transmitting plant, and the remainder, namely £1 740, for power-factor-improving plant.

The latter has to inject about 600 kVA. There are various ways in which this may be done. If there are some large motors among the consuming devices we might provide them with slip-ring phase advancers, or we might use synchronous motors, or self-starting synchronous induction motors, or we may provide squirrel-cage motors with static condensers, or we may use a combination of such means. The essential condition is that we must keep within the permissible expense of £3 per injected kVA. In other words we must not depart too widely from the rule $\sin\phi = \alpha$.

### THE EFFECT OF POWER FACTOR ON THE WORKING COST OF GENERATION AND TRANSMISSION.

Whilst the peak load factor of consumers mainly influences capital outlay and efficiency, a bad power factor at lighter loads increases the cost of generation per unit. There is, morever, a reduction in the efficiency of generating and transforming plant. Both have certain losses, such as iron, friction and windage losses, which are dependent on their size but are independent of load, so that the overall efficiency of prime mover, generator and transformer is reduced by bad power factor. It must also be borne in mind that with small load and large kVA output more units must be kept in commission than would suffice with a good power factor; hence working costs are thereby increased. It is therefore to the supply company's interest that the consumer should have a good power factor not only at peak load, but also at lower loads.

The apparatus used for power factor improvement has already been briefly mentioned and will now be considered in somewhat greater detail.

### THE ROTARY CONDENSER.

Over-excited idle-running machines employed solely for power factor improvement are not generally used by consumers. The only apparatus of this type I have seen was erected in 1896 by advice of the late Mr. Dobrovolsky at the Oerlikon engineering works in connection with the Buelach–Oerlikon transmission (23 km, 15 000 volts at first, later increased to 30 000 V) and this supplied current to the motors in the works. The firm informed me that a similar machine was at the same time supplied to the works of Messrs. Escher, Wyss and Co. in Zurich.

Recently two rotary condensers, each with an output of 3 000 kVA, have been installed by Mr. A. Dickinson* in connection with the Bombay hydro-electric works at the delivery end of the 100 000 V feeders.

Similar plant, but on a much larger scale, has been installed by the General Electric Company of America in connection with power transmission over very long distances.† Here the main object is phase adjustment, as explained in the beginning of this paper. The largest machine yet built has a capacity of 30 000 kVA when used to advance the phase of the current, and 20 000 kVA when used to retard the phase. It is a 10-pole three-phase 6 600-volt alternator running at a constant speed of 600 r.p.m. The following particulars taken from the text and the illustrations in the publication cited are of interest. The machine has salient poles in the rotor, the stator being the armature. The rotor has a diameter of 2·45 m and its core length is 2·05 m. The circumferential speed is no less than 77 m per second. The exciter is a 150 kW compound-wound generator giving a maximum current of 600 amperes for over-excitation. Thus only 0·5 per cent of the maximum kVA output is required for excitation. The output coefficient is 3·5 when the machine acts as a condenser, and 2·35 when it acts as a reactance. It is made self-starting by a damper winding on the rotor supplied by 30, 37½ and 45 per cent taps from the transformer. The damping winding during the start shields the main exciting winding from the effect of the rotating stator field, which would otherwise produce an excessive voltage in the exciting coils. To reduce the mechanical resistance at starting (which is due to the oil being squeezed out when the machine is at rest) oil under pressure is forced beneath the journals to make them float in oil before starting. The bearings are water cooled and the whole machine is cooled by air blast, the volume of air required being 37 $m^3$ per second. The temperature guarantees are a rise of 50 degrees C. in the stator and 80 degrees C. in the rotor measured by thermometer, and 10 degrees C. more if measured by thermo-couple.

Two smaller machines (each 12 000 kVA) were supplied by the same makers in connection with the 22 000-volt transmission of the Andhra Valley Power Company, Bombay. Owing to the higher ambient temperature (45·5° C.) the temperature-rise is limited to 45 degrees C. in the stator and 55 degrees C. in the rotor.

The author is not aware of any instance where a consumer drawing his supply from a thermic works has put up a rotary condenser on his own premises for power factor improvement; and the reason is not far to seek. The consumer has to pay not only for the energy he consumes in his motors, but also for that which he wastes in his rotary condenser, and that is a considerable amount. A rotary condenser of some hundreds of kVA cannot be worked with a smaller loss than a generator of equal output. The loss in kW may be somewhere between 6 and 7 per cent of the output in kVA. To realize what this means financially we may go back to the case of the private works of 1 000 kW peak load. At full load of 600 kVA (leading) the machine would require a supply of about 36 kW to cover its own losses; and although by decreasing the excitation to adapt the condenser to light-load conditions the copper loss in the armature might be decreased, all the other losses would remain the same, so that on the whole the loss would remain very much the same. Moreover, the attempt to economize by constant attention to the changing load conditions would introduce some extra cost of labour. We may thus base the financial argument on the supposition that the number of kW required to cover condenser losses remains constant during the whole time the installation is in use. With a load factor of 26½ per cent this means 2 300 hours per annum. In a year the rotary condenser would therefore waste 83 000 units. The energy supplied to the motors or other consuming devices amounts to 2 300 000 units. The energy wasted is therefore about 3·6 per cent of the energy utilized. If the load factor were lower than here assumed the percentage of wasted energy might exceed 4 per cent. It must also be borne in mind that the rotary condenser requires oil and renewal of brushes, perhaps occasionally some repairs, and certainly some slight amount of attendance. For interest, depreciation, maintenance and petty materials it is customary to reckon 15 per cent. With the machine costing (exciter and switchgear and foundation included) £3 per kVA, or in all £1 800, these charges come to £270, to which must be added labour, which we shall not overestimate at £1 a week, thus bringing up the annual cost to £322. At 1d. per unit the charge for the supply would be, in round figures:

---

* *Journal I.E.E.*, 1915, vol. 53, p. 693.

† *General Electric Review*, 1920, vol. 23, p. 160.

| | |
|---|---|
| Useful energy .. ... | £9 600 |
| Wasted energy .. .. | £346 |

To the latter figure must be added the £322, so that the rotary condenser costs annually £668, and to make in this case power factor improvement by rotary condenser a commercial proposition the supply company would have to give a rebate of at least 8 per cent. This is impossible. We may therefore consider the installation of rotary condensers by consumers to be financially unsound.

That rotary condensers are successfully used by supply companies is not due to financial reasons, but to the absolute necessity of giving their distant consumers a constant-voltage supply, for which purpose, in the present state of the art, the rotary machine is the only available apparatus.

### The Static Condenser.

A condenser for power factor improvement as made by Messrs. British Insulated & Helsby Cables, Ltd., is composed of elements each of about 1 $\mu$F capacity suitably grouped to obtain the total capacity required and housed under oil in a tank, much in the same way as a transformer. Also, like a transformer, the static condenser requires no attention and has in this respect a great advantage over any rotary machine. It has the further advantage that its own waste of energy is exceedingly small. The limiting safe voltage on an element of the type mostly used is given by the makers as 600 V, but for certain purposes elements of smaller capacity with a safe voltage limit of 750 V are also made. The number of elements required depends on the terminal voltage, current and frequency.

Let $E$ be the terminal voltage, $\omega$ the circular frequency (for the usual periodicity of 50, $\omega = 314$), $P$ the desired leading kVA, $c$ the capacity of one element in microfarads, and $e$ the permissible voltage per element; then a simple calculation shows that the total number of elements is

$$n = \frac{P10^9}{\omega c e^2}$$

The cost varies inversely with the frequency and the square of the voltage per element. If the consumer's terminal voltage is sensibly less than 600 V it can be brought up to this figure by an auto-transformer. If it is more, it can be brought down to 600 V or up to a multiple of 600 V by the same means.

The power factor of a condenser is very small and, consequently, its inherent loss correspondingly low. The makers claim that it amounts in kW, on an average, to 0·5 per cent of its output in kVA. If a transformer is required there is, of course, an increased loss.

Fig. 1 shows the relation between temperature and power factor for different types of element, oil-immersed and tested at 250 volts and 50 frequency. In actual work the temperature-rise is stated by the makers to be 11 degrees C.

The control apparatus of static condensers consists mainly of oil-immersed switches with auxiliary contacts short-circuiting the condenser when the main switch is opened, and the usual no-volt and overload release and an ammeter.

The following data as to cost have been supplied to the author by the makers for a condenser equipment of 100 kVA output, including tank and switchgear, all at 50 frequency.

| | | | |
|---|---|---|---|
| Voltage on supply terminals .. ... ... | 600 | 440 | 440 |
| Transformer .. .. .. .. .. | Not used | Used | Not used |
| Condenser voltage .. .. .. .. | 600 | 600 | 440 |
| Cost .. .. .. .. ... .. | £336 13s. 4d. | £468 8s. 4d. | £580 5s. 11d. |

### The Synchronous Induction Motor.

The practical application of the idea of using the same machine for the double purpose of providing motive power and at the same time injecting leading kVA into the supply terminals dates back some 30 years, when the Oerlikon Company employed a few such motors in their own shop, the current being derived from the Buelach line already mentioned. It is, of course, convenient that a motor for this purpose should be made self-starting and self-synchronizing. If the machine is provided with a wound rotor, like an induction motor, it can be started with a resistance inserted in the rotor circuit, and when it is nearly up to speed a direct current can be passed through the rotor winding so as permanently to magnetize the poles and convert it into a synchronous motor. In order that the motor

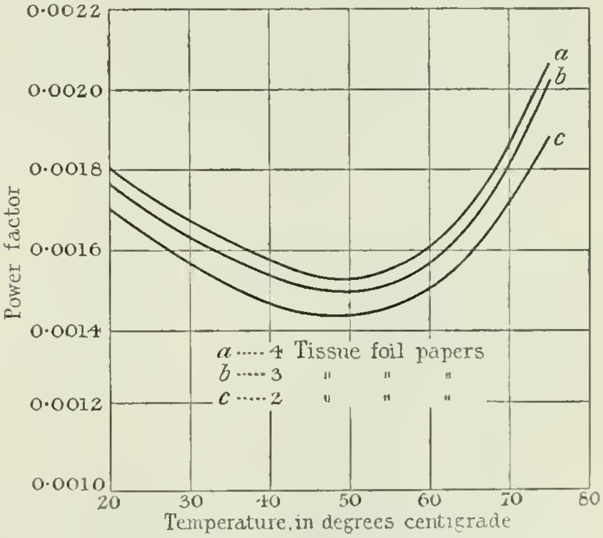


Fig. 1.—Power factor tests on Helsby condenser elements; made at 250 volts and 50 cycles.

when so excited shall jump into synchronism the slip must be small and the moment of inertia not too great.* Almost every dynamo maker is ready to supply such motors.

The various makes differ in detail, but the main principle is the same. In some cases the direct current can be applied during the starting period, so that the process of starting is as simple as with an ordinary induction motor.

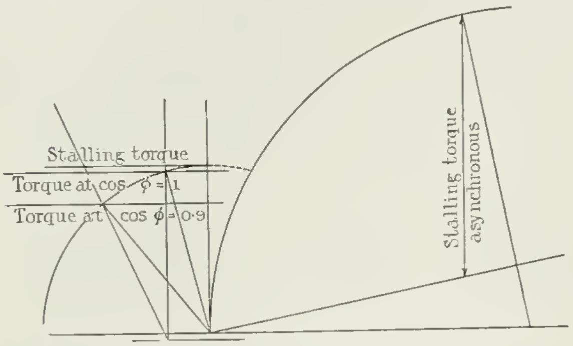


FIG. 2.—Locus diagrams of synchronous induction motor (original power factor 0·89).

The rotor may have salient poles as in an alternator, or it may have non-salient poles. In the former case the starting torque is smaller than with a non-salient-pole type; and for this reason, as also for the convenience of using standard frames and stampings, it is generally found that to convert the induction motor to synchronous working is more advantageous than the opposite process, namely, to start with the design of a synchronous machine and convert it into an induction motor.

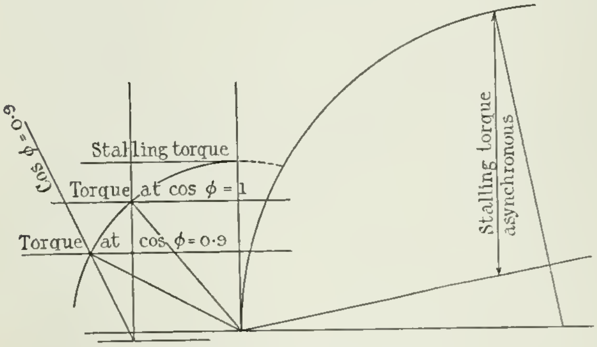


FIG. 3.—Locus diagrams of synchronous induction motor (original power factor 0·73).

The working condition of the motor can be represented by a circle diagram much in the same way as that of an ordinary induction motor, only that in the self-starting motor we have two locus curves, the one for the synchronous and the other for the asynchronous condition. With d.c. excitation fixed at a value just sufficient to give full load at unity power factor (with no saturation in the teeth), the locus for the synchronous condition has a smaller radius. The original power factor of the induction motor to be converted has a considerable influence on the stalling torque in the synchronous condition. This will be seen from Figs. 2 and 3, drawn approximately to scale for the same excitation at all loads, and therefore the same heating in the rotor.

In Fig. 2 the natural power factor of the induction motor is 0·89 and in Fig. 3 it is 0·73. In both diagrams the vectors are inserted for unity and 0·9 leading power factor. Taking as a datum for comparison the torque of the induction motor as 100 in both cases, the diagrams show the following working conditions for constant excitation :

| | | |
|---|---|---|
| Original full-load power factor .. | 0·89 | 0·73 |
| Full-load torque .. .. .. | 100 | 100 |
| Torque at unity power factor .. | 100 | 86 |
| Torque at 0·9 leading power factor | 84 | 53 |
| Margin to stalling torque in the synchronous condition | Practically none | 27 |
| Margin to stalling torque in the asynchronous condition | 70 | 73 |

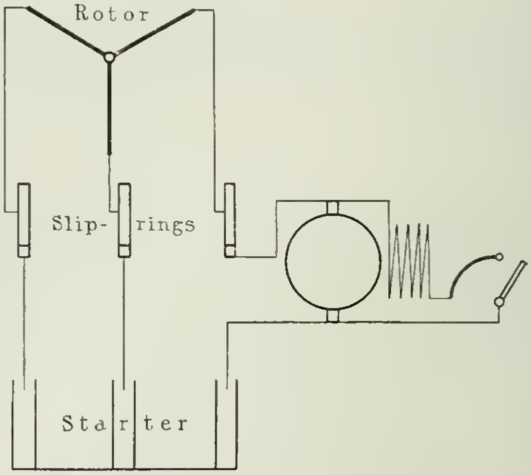


FIG. 4*a*.—Method of starting a synchronous induction motor (British Westinghouse, 1913).

The dotted part of the synchronous locus circle indicates an unstable condition. When the motor falls out of step it continues to run as an asynchronous motor. It synchronizes again when the load has fallen below stalling load. If the motor is designed for full load at 0·9 power factor it will not fall out of step so easily, but then its kVA capacity must be greater than that of an ordinary induction motor. For this reason, and also because an exciter is required, the cost of a synchronous induction motor must always be greater than that of an ordinary induction motor; and the difference in cost must be the greater the smaller the leading power factor required for full normal load. Examples are given later. Two conditions are necessary for a motor to self-synchronize, namely, a small natural slip and a small mechanical moment of inertia. Modern practice is to put sufficient copper into the rotor to make the slip about 1 per cent and to keep down the moment of inertia to the lowest possible value; then the motor readily synchronizes, even under load or overload.

---

* See paper by E. ROSENBERG, *Journal I.E.E.*, 1913, vol. 51, p. 62.

The switchgear between the rotor slip-rings and the starter is shown diagrammatically in Fig. 4 for some of the systems adopted by various makers. Fig. 4*a* illustrates the simple arrangement in which the direct current is passed down one phase and up the other two in parallel. The stator circuits are not shown. The stator may, in order to reduce disturbance of the line at starting, be arranged in the well-known way for starting in star and running in delta; but this is applicable to all types and need not be considered here.

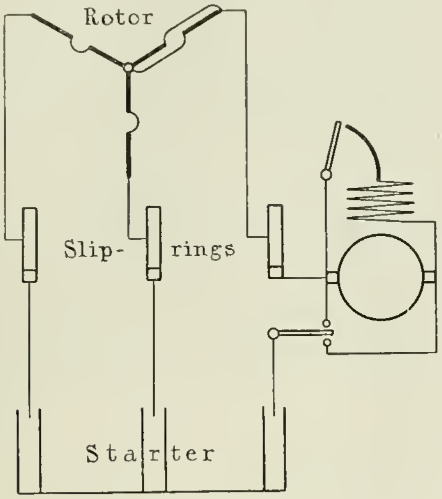


FIG. 4*b*.—Method of starting an Oerlikon synchronous induction motor.

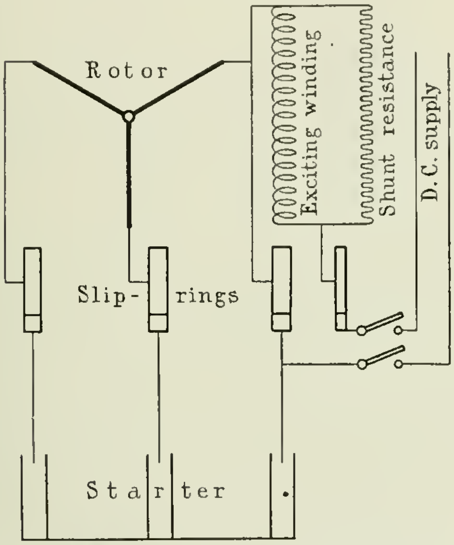


FIG. 4*c*.—Method of starting a Siemens-Schuckert synchronous induction motor.

If the rotor has a three-phase winding it is obvious that one phase must carry the full exciting current, whilst the other two phases each carry half of it. Let $n$ be the number of turns and $\rho$ the resistance per phase, then the loss of power in the three phases when working asynchronously with a phase current $I$ will be $3\rho I^2$, and the axial excitation will be $2nI$.

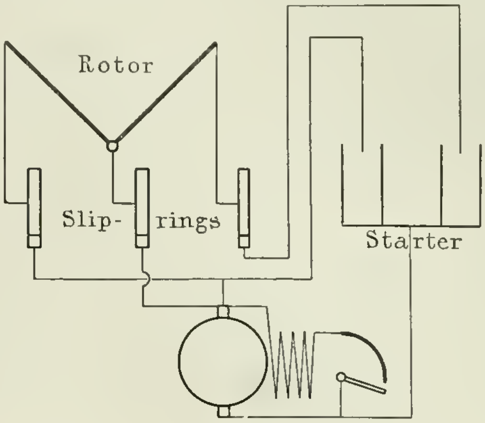


FIG. 4*d*.—Method of starting a Crompton synchronous induction motor.

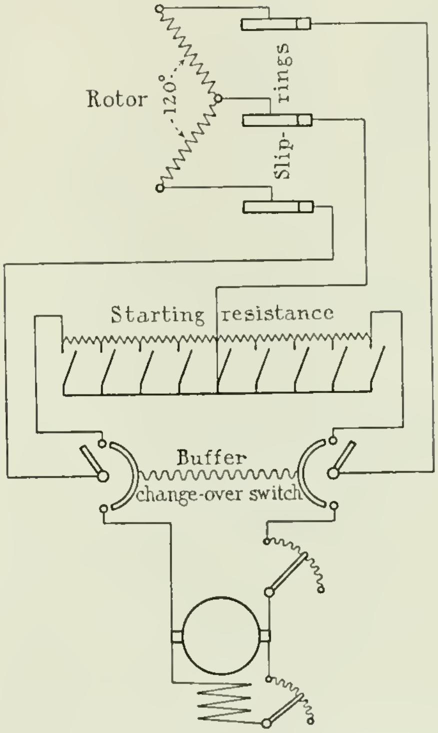


FIG. 4*e*.—Method of starting a Lancashire Dynamo and Motor Co. synchronous induction motor.

Let $i$ be the direct current to produce the same loss; then we have

$$1{\cdot}5\rho n i^2 = 3\rho n I^2 \quad \text{and} \quad i = \sqrt{2}I$$

The exciter must therefore give about 40 per cent more current than the normal slip-ring current in the asynchronous condition. The axial excitation produced will be about 5 per cent greater, but as the rotor teeth must be well saturated there is no proportional increase in the field. On the other hand there is unequal local heating. To get over this difficulty the Oerlikon plan (Fig. 4*b*) is to arrange the winding in one phase in two parallels, each of $\frac{1}{2}n$ turns. Then the heating is uniform all over the rotor and the excitation is the same as with alternating current. The exciting current is double the alternating current at the slip-rings. In the asynchronous condition the halving of the number of turns in one phase introduces some dissymmetry, but as there is always plenty of starting torque this is of no importance.

In a system devised by Messrs. Siemens-Schuckert (Fig. 4*c*) we find an attempt to reduce the amount of direct current for excitation by providing a separate winding for excitation, having a larger number of turns than the three-phase winding. The rotor has salient poles, but with the pole-shoes so wide (95 per cent of the pole-pitch) that the starting winding, which is housed in the pole-shoes, acts almost as in a motor with non-salient poles. The exciting winding is, as in any synchronous machine, placed on the magnet cores and the excitation is so great as to produce a high degree of saturation in the rotor teeth. At starting, a very high voltage is induced in the exciting coils, so that it is necessary to introduce for its protection a shunt resistance permanently coupled in parallel with it. This resistance has to be carefully selected so that on the one hand it shall lower the terminal voltage over the exciting coils sufficiently and, on the other, it shall not absorb too large a proportion of the power supplied by the exciter.

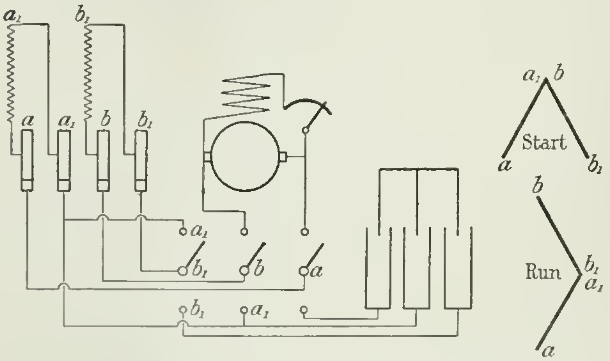


FIG. 4*f*.—Method of starting an English Electric Co. synchronous induction motor.

The exciting arrangements employed by the Metropolitan-Vickers Company have recently been dealt with in Mr. Carr's paper* and therefore need not be described in detail here. They are all more or less amplifications of the principle shown in Fig. 4*a*.

Messrs. Crompton use a two-phase winding on the rotor, with the star point carried to a slip-ring, so that, in all, three slip-rings are required. The advantage of this arrangement is that, although there may be a high voltage on the two outer slip-rings, the voltage on the neutral or star slip-ring, and therefore on one terminal of the exciter, is no higher than the exciting voltage, as will be seen on tracing out the exciter circuit (Fig. 4*d*). Thus the whole of the exciter is protected from the open-circuit slip-ring voltage. A further advantage is that the whole of the rotor copper is loaded to the same current density. The makers claim that the machine in its asynchronous condition will start against 2½ times full-load torque. The exciter is permanently in circuit and, by adjustment of its shunt rheostat, the leading power factor at various loads can be regulated.

The standard type of starting and synchronizing gear used by the Lancashire Dynamo and Motor Co. is shown diagrammatically in Fig. 4*e*. The rotor has also a two-phase winding, but with 120° angular displacement of the phases, each acting at starting as an independent single-phase winding, whilst at synchronism the middle slip-ring is out of circuit so that the two windings give together an excitation equal to $\sqrt{3}$ times the ampere-turns of one phase. The change-over from the asynchronous to the synchronous condition is made via a "buffer resistance," as will be seen from the diagram.

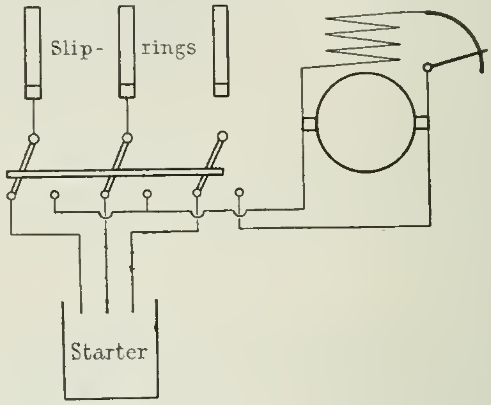


FIG. 4*g*.—Method of starting a General Electric Co. synchronous induction motor.

By an ingenious arrangement of change-over switchgear the English Electric Co. obtain the advantage of the full starting torque due to a three-phase rotor, combined with equal current loading in all the rotor copper when the rotor acts as a single-axis field magnet. The rotor has only two phases, but these may be coupled to form an open delta for starting, when the electrical angle between the two phases is 60°, and by reversing one phase the electrical angle may be altered to 120°, when the excitation given is $\sqrt{3}$ times the ampere-turns in one phase.

The arrangement is shown diagrammatically in Fig. 4*f*. There are 4 slip-rings marked a, $a_1$ and b, $b_1$ corresponding to the four terminals of the A and B phases (in open delta the third phase is omitted). To facilitate the tracing out of the connections the switch contacts are similarly labelled. The small key diagrams show vectorially the connections for "start" and "run." At starting the switch is on the lower contacts, and after all the starting resistance has been short-circuited the switch is thrown on to the upper contacts.

Fig. 4*g* shows diagrammatically the exciting circuit adopted by the General Electric Co. for their synchronous induction motors. The rotor is star connected, and the connection with the exciter is such that one phase carries the total exciting current, whilst the other two phases each carry half that current. Strictly speaking, the one phase may therefore be called overloaded; but in reality it is not so. It would be more correct to say that the other two phases are underloaded. This is, however, an unavoidable consequence of the necessity of restricting the slip to a smaller value than in an ordinary induction motor in order to ensure quick and certain synchronizing, so that the extra copper in the rotor would have to be provided in any case.

---

* *Journal I.E.E.*, 1922, vol. 60, p. 165.

### Construction and Performance of some Synchronous Induction Motors.

A characteristic feature in the design of all such motors is that to ensure stability the air-gap is made larger than in ordinary induction motors. A further characteristic is that the rotor teeth are highly saturated. Otherwise there is no important difference in the magnetic circuit, so that the same type of frame may be used for either the synchronous or the asynchronous motor. Electrically there is the difference that, with a view to quick and certain synchronizing, more copper is put into the rotor, and the current-carrying capacity of the slip-rings and their brushes must be greater. Short-circuiting of slip-rings is impossible. In most motors some excitation may be left on during the starting period. The synchronous stalling torque is always smaller than the asynchronous, but when the load torque exceeds the former the motor runs on as an asynchronous machine with a low, lagging power factor until the load has fallen, when the motor again jumps into step. The efficiency is a little lower owing to the greater loss in excitation. The open slip-ring voltage is higher than in an ordinary induction motor and may reach 2 000 volts.

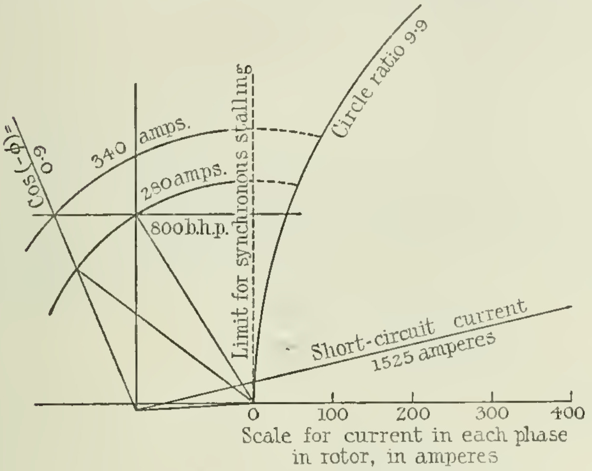


Fig. 5.—Circle diagram of 800 b.h.p. Crompton synchronous motor; 2 200 volts, 25 cycles, 250 r.p.m.

The following data will serve to give a more precise meaning to the above general statements.

*800 b.h.p. Crompton motor:* 2 200 line volts; 25 cycles; 250 r.p.m. stator three-phase; rotor two-phase; air-gap 4·5 mm; open slip-ring voltage 1 300 V to earth; exciting current per phase, according to load and power factor, up to 340 amperes, or 680 amperes on the star-point slip-ring. The circle ratio (ideal short-circuit current divided by open-circuit current) is 9·9. From the locus diagram (Fig. 5) the working condition at any power factor and load can be determined.

The following table is given by the makers to show the performance of this motor:

| Output | Line volts | Line current | Exciting power | Efficiency* |
|---|---|---|---|---|
| b.h.p. | V | A | per cent | per cent |
| 800 | 2 200 | 168 | 1·7 | 93 |
| 800 | 2 200 | 188 | 2·9 | 92 |

* At half-load the efficiency is 1 per cent lower.

The makers state that the increase in cost over an ordinary induction motor would be approximately 20 per cent when designed for unity power factor, and 30 per cent for 0·9 loading power factor.

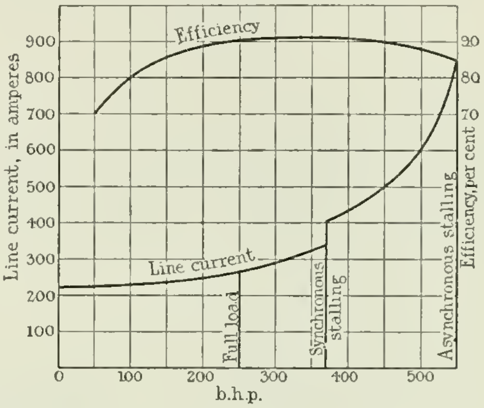


Fig. 6.—Performance curves of 250 b.h.p. Oerlikon synchronous induction motor; 500 volts, 50 cycles, 750 r.p.m.

*Motors of the Lancashire Dynamo and Motor Co. Ltd.*—The salient-pole type (used when only a light starting torque is required) has a starting winding housed in the pole-shoes, and this winding also acts as a damper to protect the field winding from excessive voltage. For heavy starting torque the non-salient-pole type is used, but has no additional squirrel-cage winding, as the field winding itself acts as a starting winding. Dampers are generally not required, but, if desirable, a damping effect may be produced by short-circuiting part of the rotor winding. The open slip-ring voltage varies between 1 400 and 2 000. The non-salient-pole type is started in the manner shown in Fig. 4*e*. The individual switches in the solid starter resistance are successively closed by a reciprocating motion given by hand to a starter handle which, in its last movement, also puts the motor into synchronism by first connecting up the resistance (marked "buffer" in the diagram) across the rotor terminals, then taking the rotor off the starter resistance, switching it on to the exciter circuit and finally opening the buffer circuit. A second handle serves for returning the starter to the starting position.

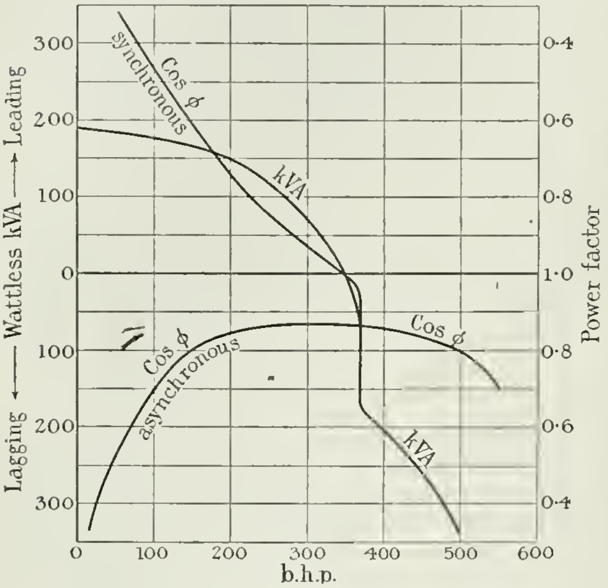


FIG. 7.—Performance curves of 250 b.h.p. Oerlikon synchronous induction motor; 500 volts, 50 cycles, 750 r.p.m.

Interlocks are provided for preventing the closing of the main stator switch unless the starter is in the starting position. As regards the excitation required for 0·9 leading power factor motors, the makers have given me the following examples:

650 b.h.p. exciter: 400 amperes, 40 volts
320 b.h.p. exciter: 230 amperes, 60 volts

The increase in cost of the synchronous over the asynchronous machine is largely dependent on the amount of power factor correction required. Taking, however, the usual case that a leading power factor of 0·9 is desired, the makers estimate that the increase may be taken to be one-third the cost of an asynchronous motor of the same power.

250 *b.h.p. Oerlikon motor:* Terminal voltage 500; 50 cycles; 750 r.p.m.; 0·9 leading power factor. The starting resistance is solid (the starter shown in Fig. 4*b* has been represented as a liquid starter merely to preserve as far as possible uniformity of representation) and the two-way switch in Fig. 4*b* is replaced by the usual three-phase starting switch worked by a handwheel. Another hand-wheel serves to adjust the excitation. The starting and regulating gear is housed in a cast-iron case permanently attached to the motor frame. The exciter is mounted overhung on the motor shaft. The performance of the motor is shown by the curves in Figs. 6 and 7.

550 *b.h.p. English Electric motor:* Terminal voltage 1 000; 50 cycles; 428 r.p.m.; unity power factor at full load and leading power factor at smaller loads; constant excitation at 44 volts, 220 amperes; synchronous stalling point at 1·7 times full load. The tooth density is very high, so that there is a great difference in the rotor current when the motor works asynchronously and when it works synchronously with d.c. excitation in the rotor. The high saturation makes the field stable, and the fact that the axial excitation is provided by two coils with their axes 120° (instead o 180°) inclined to each other has a beneficial effect on the field form. Fig. 8 shows the locus curves of this motor, and Fig. 8*a* the performance curves.

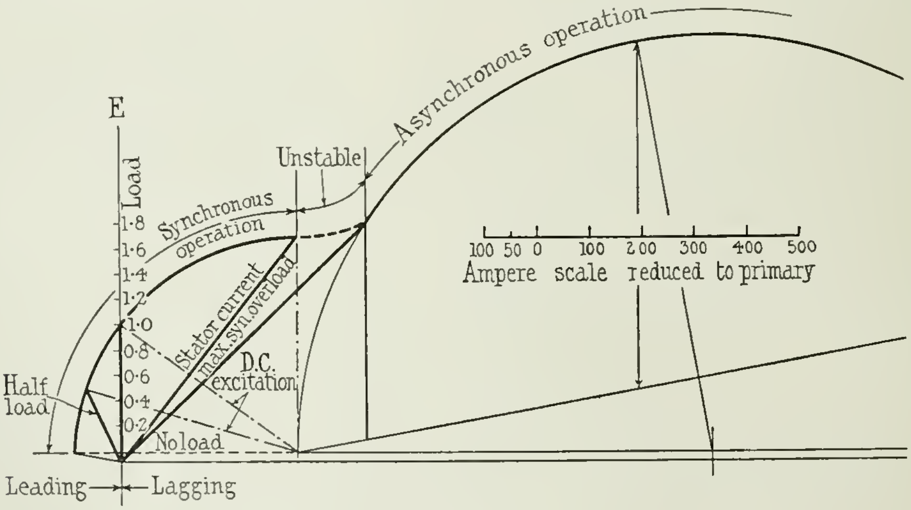


FIG. 8.—Circle diagram of an English Electric Co. 550 b.h.p. motor.

250 *b.h.p. General Electric motor:* Terminal voltage, 440; 50 cycles; power factor from unity to 0·9 leading at full load, according to excitation; 375 r.p.m.; open slip-ring voltage, 1 140; slip, 1·06 per cent; diameter of armature, 120 cm; core length, 25 cm; air-gap, 2·5 mm. The exciter is mounted on the motor shaft and has a maximum output of 5·6 kW.

Fig. 9 shows the performance of this motor as a function of the output in brake horse-power. A and B are power-factor curves at constant excitation; C is the efficiency curve if the excitation is adjusted to give unity power factor at all loads, and D is the efficiency curve if the excitation is adjusted to unity power factor at full load, but not varied for smaller loads.

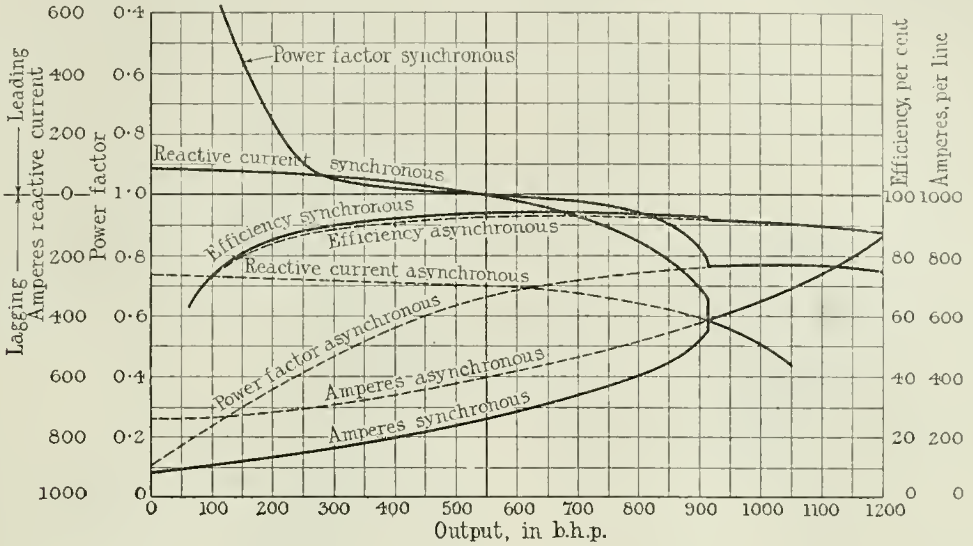


FIG. 8*a*.—Performance curves of an English Electric Co. 550 b.h.p. motor.

*225 b.h.p. Sandycroft single-field cascade motor.*—The stator in Mr. Hunt's self-starting synchronous cascade motors (Fig. 9*a*) is provided with two star-coupled windings in parallel, and the d.c. excitation is introduced between the two star points.* The rotor winding consists of a six-sided mesh with star coils tapped into it at equally spaced points. The terminals of these coils are brought out to six slip-rings. Opposite rings are connected in pairs across three independent starting resistances. The currents through the rotor windings are symmetrical and no second field can therefore be produced. The motor designed for an (8 + 4)-pole cascade is started as an 8-pole machine and when near synchronism three of the slip-rings are short-circuited and the remaining three are open circuited. This action converts the winding into an interconnected star-mesh system and results in the production of an auxiliary 4-pole field. The switch used for changing the rotor connections also connects the star points of the two parallel stator windings to the d.c. exciting circuit, producing a stationary 4-pole field. At synchronism the 4-pole rotor field rotates relatively to the rotor iron at 500 r.p.m. and, as the rotor itself has the same forward speed, the two 4-pole fields in stator and rotor are stationary in space and lock together so that the motor works as a synchronous 12-pole machine. Efficiency and power-factor curves are sown in Fig. 9*b*.

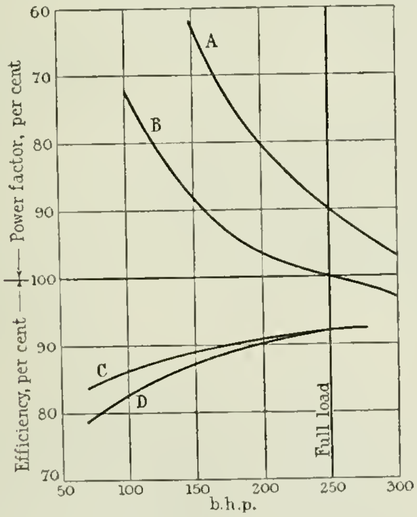


FIG. 9.—Performance curves of a General Electric Co. 250 b.h.p. motor.

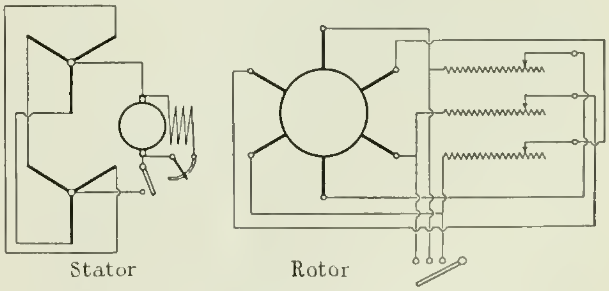


FIG. 9*a*.—Connections of a Hunt (8 + 4)-pole cascade motor.

THE ROTARY CONVERTER AS POWER FACTOR IMPROVER.

At first sight the rotary converter appears to be an admirable appliance to inject leading kilovolt-amperes into the supply line, but on closer consideration of its working condition it will be found that its use in this direction is rather limited on account of the rapid increase of the copper losses in the armature with an increase of the wattless component given to the line. The increase in output of a rotary converter as compared with a simple d.c. generator is due to the fact that the armature winding has to carry only the difference between the motoring alternating current and the generated direct current. For unity internal power factor this difference is a minimum. The external power factor at the terminals is then about 0·98 lagging. To get unity at the terminals the internal power factor must be of the order of 0·98 leading. To get a leading power factor at the terminals the internal power factor must be correspondingly smaller, which means that the wattless component must be larger. Since the amount of heating increases as the square of the wattless component, it follows that power factor improvement can only be obtained at the sacrifice of output. The copper loss in a six-phase converter is smaller than in a three-phase one, and, if we refer the increase of losses due to the leading current to the normal loss at unity power factor, we find that the percentage increase of loss is larger in a six-phase than in a three-phase converter. Thus if the field excitation is increased so as to induce a 30 per cent wattless component, the copper loss for full output would be increased by about 18 per cent in a three-phase and by about 30 per cent in a six-phase converter. To keep within the heating limit the output would therefore have to be reduced to 92 per cent and 88 per cent respectively of the permissible output at unity power factor. This is rather a high price to pay for the injected kilovolt-amperes. Economically it is better not to use the converter for giving to the line leading kVA, but to be content with taking from the line true kW and thus raising the general power factor of the system by increasing the watt load. Moreover, a converter excited to unity power factor will scarcely influence the line voltage at all, whilst a converter injecting leading kVA may have some disturbing influence.

---

* See paper by Mr. L. J. HUNT, *Proceedings of the South Wales Institute of Engineers*, vol. 35, p. 309.

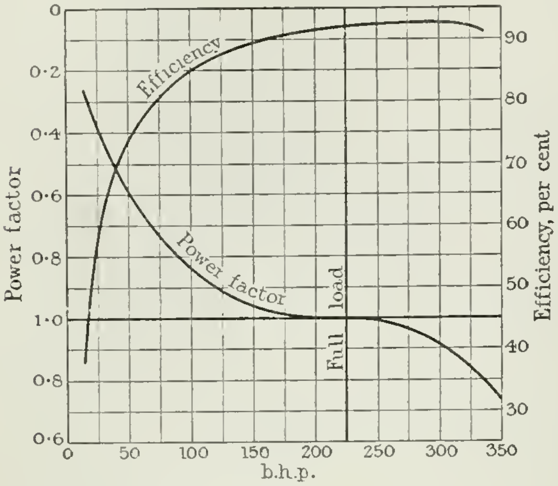


FIG. 9*b*.—Performance curves of a 225 b.h.p. Hunt (8 + 4)-pole cascade motor.

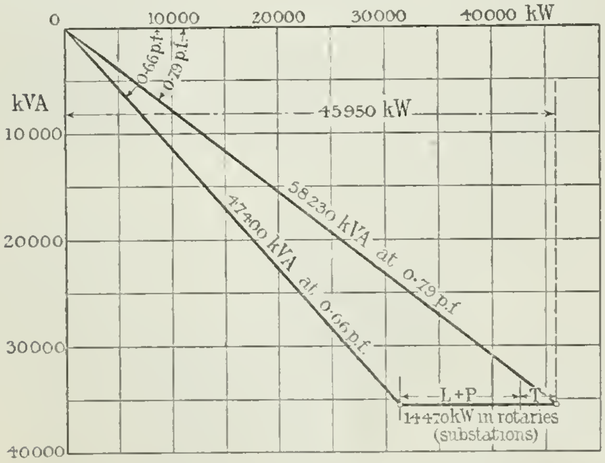


FIG. 10.—Load vectors of Birmingham electric supply.

As an example of the beneficial influence of a converter load on a general supply system we may take that of the City of Birmingham, to whose engineer, Mr. R. A. Chattock, the author is indebted for the following particulars and for the vector diagram shown in Fig. 10. The total capacity of the rotary converters is 9 800 kW at unity power factor. All rotary converters are provided with means to vary their power factor down to 0·97 leading, but Mr. Chattock considers it hardly safe to go beyond this. Generally the converters are worked at unity power factor.

The power factor improvement is shown in the following table referring to the time of heaviest load, which occurred at 4.30 p.m. on the 17th December, 1920. In the vector diagram P and L mean d.c. power and lighting load, and T means traction load.

| | |
|---|---|
| Total a.c. load on all generating stations | 58 230 kVA at 0·79 power factor. |
| Substations' load, at the same time, taken up by all substation rotary converters running at approximately unity power factor, of which 11 213 kW is power and lighting and 3 261 kW is traction | 14 474 kW. |
| Estimated e.h.t. supply outside substations on 17 December, 1920 | 47 400 kVA at 0·66 power factor. |

### SLIP-RING PHASE ADVANCERS.

If an electromotive force of slip frequency is introduced in the correct sequence into the slip-rings it will shift the rotor current forward. To ensure that the injected E.M.F. shall have the correct frequency, the rotor current itself is made to generate it; and to ensure the correct sequence is merely a question of making the appropriate connections between the phase advancer and the slip-rings. The interaction between the stator and rotor causes the leading kVA injected into the rotor to be translated into the line, and thus a comparatively small amount of kVA given to the rotor becomes a large amount of leading kVA given to the line. We may take as an example a 500 kW motor with, say, 1·5 per cent slip. If it is desired to inject into the line 50 per cent of the true power as wattless kVA, the line would require a supply of 250 leading kVA. The working condition of the motor would not be altered; the slip and the overload capacity would remain as they were. If we inject a certain amount of leading kVA into the rotor the working condition of the motor will be altered. The slip must increase because the slip E.M.F. must now cover not only any additional ohmic loss, but also the quadrature component of the E.M.F. of the phase advancer. The slip of 1·5 per cent may thus become increased to 2·5 per cent and the translating ratio of the interaction between stator and rotor will no longer be 100 to 1·5, but 100 to 2·5. That is to say, for every kVA injected into the rotor the line benefits by 40 kVA. Neglecting losses, which are very small, a phase advancer having an output of 6·3 kVA will benefit the line to the same extent as a static or rotary condenser giving it 250 kVA. At the same time the overload capacity of the motor is increased.

There are two types of slip-ring phase advancer in use: the rotary and the oscillatory. The former is an a.c. commutating machine which must be driven from some external source of power, the latter is a d.c. machine which requires no external driving, but needs d.c. excitation from an external source.

### Rotary Type of Phase Advancer.

The general principle of the rotary phase advancer is shown in Fig. 11 for a 2-pole three-phase machine. A, B, C are the stator exciting coils (the diametrically opposite poles are not shown, in order to avoid complication), R represents the armature, and K the commutator with the three brushes, a, b, c. In the position shown, the brushes are in the polar axes and therefore the armature exerts no torque. If the brushes are displaced in one sense, the machine gives torque in the opposite sense and acts as a motor taking power from the slip-rings, at the same time injecting a certain amount of leading kVA into the slip-rings. This property of the rotary advancer can be used in cases where the main motor is provided with a flywheel in order to cope with heavy peak loads, when a considerable slip must be allowed. Then part of the slip energy may be recovered instead of wasting the whole of it in slip resistance.

Where only phase-advancing is required the brushes remain in the axial position; the impressed flux and that created by the armature current are then in line, and by giving the armature a winding of sufficient turns the whole of the flux required can be produced by the armature winding itself, so that a stator with the coils A, B, and C becomes unnecessary.

This is the principle on which the Scherbius rotary phase advancer is constructed. The machine has no stator, but the iron core of the armature is radially extended beyond the armature conductors so that the rotor iron outside the winding performs the office of an external stator. Since the magnetic reluctance of the air-gap is thus avoided, the advantage of a strong field with only a moderate excitation is secured. On the other hand there is the disadvantage that the commutation necessarily takes place not in the neutral space, but in the strongest part of the field, making the commutation more difficult than in an ordinary d.c. machine. The fact that not a direct but an alternating current must be commutated is of little importance, because the frequency of this current is so low that the condition as regards commutation is practically the same as with direct current. The arrangement of this machine is diagrammatically illustrated in Fig. 12.

If the rotor is at rest the machine acts simply as a choking coil. The currents introduced by the three brushes produce a rotating field having an angular velocity corresponding to the slip frequency. The self-induced E.M.F. lags behind the current by a quarter period. If, now, the armature is rotated by external power with slip frequency, there is no cutting of field lines by the armature winding and the machine acts simply as a dead resistance. By increasing the impressed speed, so that the winding rotates with a speed greater than that of the field, the E.M.F. generated changes sign, that is to say, it leads relatively to the current by a quarter period. The faster the armature is driven the greater is the phase-advancing effect on the rotor currents of the motor.

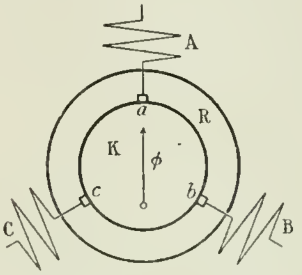


Fig. 11.—Diagram of phase advancer with field winding.

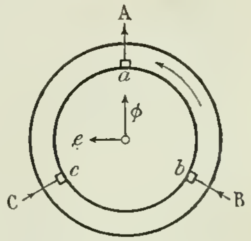


Fig. 12.—Diagram of phase advancer without field winding.

The principle on which a locus diagram of an induction motor with slip-ring phase advancer may be constructed has been given in a previous paper * and need not be repeated here. It is, however, interesting to note that the theoretical locus curve deduced on the assumption that there is no saturation is beneficially altered by so designing the Scherbius armature that at full load there shall be considerable saturation. Referring to Fig. 4 of the previous paper, ES, the ohmic voltage loss in rotor and advancer, is approximately proportional to the phase current † and also to the excitation producing the leading E.M.F., but this E.M.F. (SB in Fig. 4) is not strictly proportional to the current. As the saturation increases, the field increases only according to the magnetization characteristic, and the E.M.F. injected increases a little less than the field because with increasing load the slip increases and the excess of armature

---

* G. Kapp: "Phase Advancing," *Journal I.E.E.*, 1913, vol. 51, p. 252.

† The proportionality would be perfect if it were not for the fact that the contact-drop at the brushes and slip-rings does not follow strictly Ohm's law. For the sake of simplicity this disturbing influence is here neglected. In the discussion of the oscillating phase advancer the increase of resistance with diminishing current is, however, taken into account.

speed over the speed of the revolving field becomes a little smaller, especially if the advancer is driven by the motor itself. The effect of saturation can be taken account of in a very simple manner, whilst that of speed variation is not serious and can also be easily corrected. Let, in Fig. 13, OE be the no-load current and EC the radius of the Heyland circle. ES represents the ohmic voltage-drop in one phase. By a suitable scale it may also represent the excitation on the magnetizing characteristic Eee. With constant speed of cutting, BS represents, then, also the injected E.M.F. Draw EB and prolong to C′. This is the centre from which the larger circle of Fig. 4 (of the quoted paper) must be struck. Mark the point D on the Heyland circle so that ED represents the phase current to which the voltage-drop ES corresponds, and draw a circle with E as centre. Where this circle intersects the circle struck from C′ is the locus. EB represents the slip volts and from this can be found the slip. Having determined the slip we can calculate what small reduction in SB is required to account for diminished relative speed between the rotating flux and the rotating winding and repeat the construction. The resulting locus curve has the character shown in Fig. 13. The effect of saturation is to avoid excessive phase-advancing at heavy load and yet obtain a satisfactory power factor at lighter loads. As will be seen from the locus curve, the overload capacity is sensibly increased.

The author is indebted to Messrs. Brown, Boveri, the makers of the Scherbius phase advancer, for the following examples of the practical results achieved with these machines. In all cases the frequency is 50. The line marked " Recovery " contains the wattless leading kVA by which the lagging kVA of the motor working alone has been reduced. In some cases the reduction is great enough to make the phase angle negative. The slip is that of the motor at full load working alone; this, with phase advancing, is more than doubled. The exact increase can be calculated from the slip-ring voltage, current and recovery.

*Scherbius Phase Advancer.*

| B.H.P. of motor | 150 | 420 | 500 | 1 700 |
|---|---|---|---|---|
| Slip-ring volts .. | 300 | 635 | 770 | 1 030 |
| Injected volts .. | 10·5 | 21·5 | 25 | 14 |
| Slip-ring amperes.. | 260 | 380 | 350 | 900 |
| kVA of advancer.. | 4·7 | 14·2 | 15·1 | 22 |
| Original slip, per cent | 3 | 1·6 | 2·5 | 1 |
| Original power factor | 0·87 | 0·85 | 0·78 | 0·91 |
| Improved power factor | 1<br>— | 0·95<br>Leading | 0·995<br>— | 0·965<br>Leading |
| Recovery kVA .. | 65 | 290 | 285 | 960 |

## OSCILLATORY TYPE OF PHASE ADVANCER.

The author's phase advancer, more generally known under the name " vibrator," has already been described in his previous paper and the description need therefore not be repeated. It may, however, be of interest to note that its action is simply that of a condenser of very large capacity and that this capacity has a fixed value for every type.* Let $m$ be the mass of the armature reduced to its radius and to mass units of 9·81 kg, $\phi$ the flux in megalines produced by the external d.c. excitation, and $\tau$ the distance between armature conductors in centimetres; then a characteristic constant for any type of vibrator is

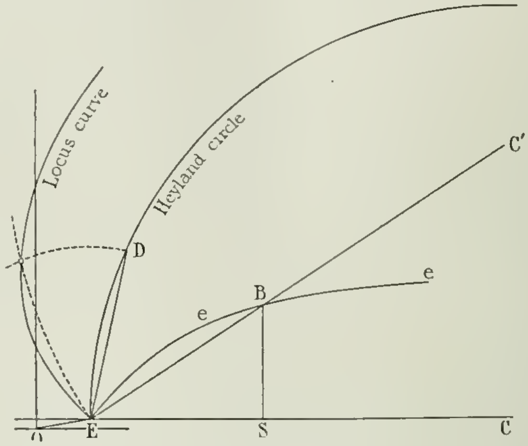


FIG. 13.—Locus curves of induction motor furnished with phase advancer.

$$B = \frac{0 \cdot 1}{m}\left(\frac{\phi}{\tau}\right)^2$$

---

* In the following note the expressions differ from those in the text mainly in that they involve $M_r$, the moment of inertia, and $Z_a$, the total number of conductors on the armature, instead of the author's $m$ and $\tau$.

The quantity of electricity in a condenser is

$$Q = \int idt = Ce$$

where $C$ is the capacity and $e$ the voltage at the terminals. In the case of the vibrator we have

$$\int Tdt = \frac{M_r\omega}{9 \cdot 81}$$

where $T$ is the torque in kilograms (force) at a metre, $M_r$ is the moment of inertia in kilograms (mass) at a (metre)², and $\omega$ is the angular velocity at any instant.

If $Z_a$ is the total number of conductors on a 2-pole vibrator, $\phi$ the flux per pole in megalines, then the instantaneous watts

$$= ei = i\frac{\omega}{2\pi}Z_a\phi \times 10^{-2} = T \times 9 \cdot 81 \times \omega$$

therefore

$$i = T \times \frac{9 \cdot 81 \times 2\pi}{Z_a\phi \times 10^{-2}}$$

also

$$\omega = \frac{2\pi e}{Z_a\phi \times 10^{-2}}$$

$$\int idt = \frac{9 \cdot 81 \times 2\pi}{Z_a\phi \times 10^{-2}} \times \int Tdt = \frac{9 \cdot 81 \times 2\pi}{Z_a\phi \times 10^{-2}} \times \frac{M_r\omega}{9 \cdot 81}$$

$$\therefore \quad \int idt = M_r \times \frac{4\pi^2}{Z_a^2\phi^2} \times 10^4 \times e$$

The vibrator therefore behaves electrically as if it had a capacity

$$C = M_r \times \frac{4\pi^2}{Z_a^2\phi^2} \times 10^4 \text{ farads}$$

Referring to the text it will be seen that $\tau = 2\pi r/Z_a$, where $r$ is the radius in centimetres at which the conductors are placed.

If now, instead of $M_r$, we write $\frac{9 \cdot 81\, mr^2}{10^4}$ to bring the expression to the units of the author, we get $C = \frac{m}{0 \cdot 102}\left(\frac{\tau}{\phi}\right)^2$.—M. W.

and the equivalent capacity of a static condenser is

$$C = \frac{1}{B} \text{ farad}$$

From this relation it follows that the leading E.M.F. injected is

$$e = B\frac{I}{\omega_s} \text{volts}$$

where $I$ is the current, and $\omega_s$ the circular slip frequency.

Although current and slip are not strictly proportional, both increase together and it follows that, even for light loads, a good power factor can be obtained with an induction motor by adding a vibrator. This is illustrated by Fig. 14 giving the power factor for a 330 b.h.p. motor when working alone and when working with a vibrator. The author is indebted for these curves to the General Electric Co. They refer to a motor supplied to the Sutton Heath and Lea Green Collieries for a line pressure of 6 000 volts, 50 cycles, and a speed of 1 460 r.p.m.

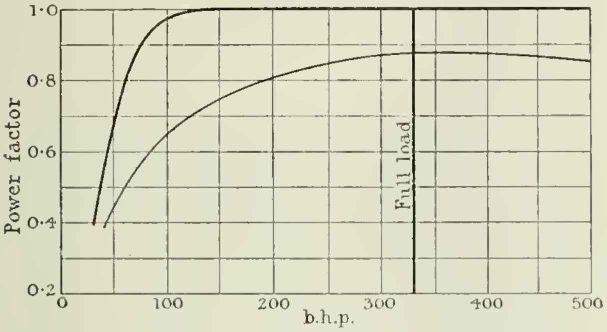


FIG. 14.—Performance curves of a 330 b.h.p. General Electric Co. motor furnished with vibrator.

The loss of power in the armature may be expressed by $\rho I^2$, where $\rho$ represents not only the armature resistance, but also the contact resistance at the brushes and the equivalent values for iron and frictional losses. Let $R_2$ be the resistance of the rotor phase, then this with the vibrator in circuit is increased to

$$R = R_2 + \rho$$

Since $\rho$ includes iron losses and mechanical friction, both of which depend on the speed, its value is not absolutely constant, though always small in comparison with $R_2$. The crest value of the speed of the armature lies generally between the limits of 600 and 1 500 r.p.m. Taking some mean value, say 1 200 r.p.m. or 20 revs. per second, we calculate $\omega$ as shown below as a first approximation and from this the crest value of the speed. If this comes out different from the first assumption of 20 revs. per second, we determine the new value of $\rho$ and from this the corresponding value of $\omega$ in a second approximation. Since the influence of a change in $\rho$ is very slight, this second approximation is generally sufficient. It is not necessary to burden this paper with the complete theory of the vibrator, but some hints as to its practical applications and the method of constructing the locus diagram may be useful. Let, for an induction motor, the Heyland circle, the circle ratio, the working point at full load, the open slip-ring voltage, the rotor current, the phase resistance and the slip be given. The question is what type of vibrator must be used to get approximately unity power factor. To design the vibrator specially for each case so as to get precisely a given power factor, either leading or lagging, is not a good commercial policy. A strongly leading power factor, although it can be obtained by a vibrator, is in any case undesirable because the large increase of rotor copper heat could no longer be compensated by the saving in the stator copper heat, so that the output of the motor would be reduced. Whether the power factor is a few per cent leading or lagging is of little importance; but what is of importance is that by the use of the vibrator a substantial percentage of the full-load kVA shall be recovered in the shape of leading kVA and given to the line. By substantial the author means anything between 40 and 70 per cent. This percentage depends primarily on the original slip and the frequency of the supply; the lower these values are, the greater is the recovery.

Let, in the following, $\omega_1$ be the circular frequency of the line, $E$ the open-circuit phase voltage of the rotor, $\omega_0$ the circular slip frequency when the motor works alone, $\omega_s$ the circular slip frequency when the motor works with the vibrator; and let

$$\beta = \frac{\cos \alpha^2,}{\sin \alpha} \text{ where } \tan \alpha = \frac{\text{injected E.M.F.}}{RI}$$

Then the following relations obtain:

Crest value of circumferential force $F = 0\cdot14\frac{\phi}{\tau} I$ kg.

Crest value of circumferential speed $v = \frac{F}{m\omega_s}$ metres per sec.

Circular frequency of slip $\omega_s = \frac{B}{R \tan \alpha}$

Increase of original slip $\frac{\omega_s - \omega_0}{2\pi}$

$$I = \frac{E}{\omega_1}\frac{B}{R^2}\beta$$

The relation between $\beta$ and $\tan \alpha$ may be taken from Fig. 15.

Having thus obtained $\tan \alpha$ we find $\omega$ and the injected E.M.F., $e = \frac{BI}{\omega}$.

The crest value of the armature speed in revs. per sec. is

$$u = v\frac{100}{\pi D}$$

where $D$, the diameter of the armature, is in centimetres. If this comes out widely different from that at first assumed, $\rho$ must be calculated afresh and the calculation for $\omega_s$, $\beta$ and $\tan \alpha$ repeated. The correction is generally small. In a rough approximation $\tan \alpha$ may also be taken to represent the ratio $\frac{\text{leading kVA injected}}{\text{kW supplied by line}}$.

But more accurately this ratio is represented by the dotted curve in Fig. 15.

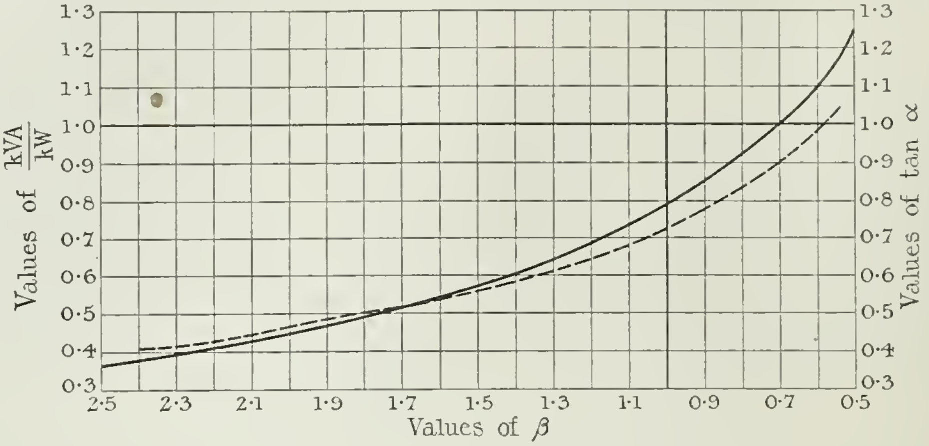


FIG. 15.—Showing the relation between $\beta$ and tan $\alpha$ in vibrator.

Fig. 16 shows to scale the locus curve for a 12-pole 1 090 b.h.p. motor provided with a 16·5 × 30 cm vibrator; terminal voltage 6 600, frequency 50, open slip-ring voltage 675, normal full-load slip 0·8 per cent. On account of this unusually small slip the power factor is slightly leading above half load, and at full load the recovery is nearly 80 per cent. The motor is direct coupled to a generator which supplies single-phase current to a circuit distinct from the general three-phase circuit.

The data of the vibrator are: Armature 16·5 × 30 cm; commutator 12·5 × 22·5 cm; mass 3·9 kg; flux 4 megalines; $B = 0{\cdot}088$. The equivalent resistance $\rho$ is not constant, but depends on the speed and the rotor current. It is given in the following table:

| | | | | | | |
|---|---|---|---|---|---|---|
| I = | 500 | 450 | 400 | 300 | 200 | 100 |
| $\rho$ = | 0·006 | 0·0063 | 0·0072 | 0·010 | 0·0165 | 0·050 |
| R = | 0·0174 | 0·0177 | 0·0186 | 0·0214 | 0·0279 | 0·0614 |

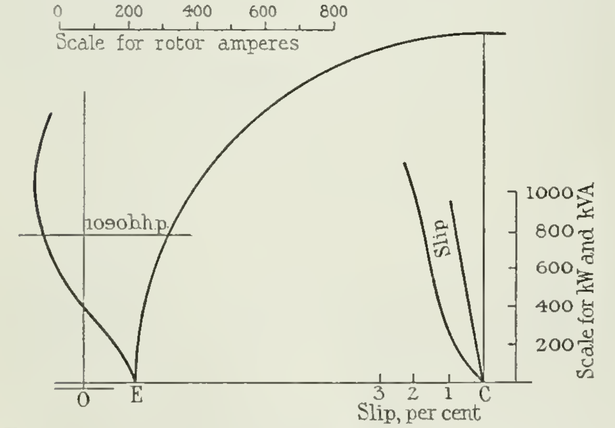


FIG. 16.—Locus curve of a 1 090 b.h.p. motor furnished with vibrator.

The rapid increase in $\rho$ at very light load is due to certain constant losses such as brush friction, iron losses and the fact that contact losses at the commutator and slip-rings do not follow Ohm's law. The effect on the locus curve is seen in its shape near the origin.

The exciting force is 5 000 ampere-turns for each armature, involving for all three armatures an expenditure of about 600 watts. From the mathematical investigation above cited it will be seen that the phase-advancing effect of the vibrator depends on the square of the flux and is inversely proportional to the mass. This points to the use of 2-pole armatures of small diameter and comparatively great length. The proportion found in practice to be suitable is about 1 to 2. Since the air-gap can be made very small the power required to produce the strong field is not very large; it varies from the smallest type ($D = 10$ cm) to the largest hitherto made ($D = 16{\cdot}5$ cm) between $\frac{1}{2}$ kW and 1 kW, which means from 0·25 to 0·1 per cent of the power of the motor.

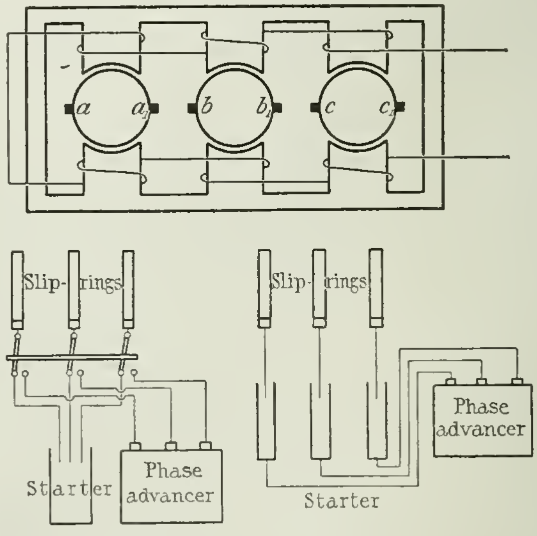


FIG. 17.—Arrangement and connections of Kapp vibrator.

The connection of the vibrator with the slip-rings may be either in star or in delta. The choice depends on which type comes nearest to the given full-load rotor current, but as a general rule delta connection is preferable because of the smaller current. As the vibrator is essentially a low-voltage machine it is advisable to make it the star point of the rotor circuit. This has the advantage that no switch of any kind is required. The starter must be insulated on all its six poles. On starting, the high-frequency current goes through the vibrator and makes its armatures merely quiver; as the slip frequency decreases they begin to oscillate, and when the starter is completely short-circuited the oscillation has reached the full amplitude. The inductance of the armatures being only a very small fraction of that of the rotor phases there is practically no reduction in starting torque when the vibrator is in circuit. Where the starter is only insulated at three poles a change-over switch must be provided which makes contact with the vibrator before it disconnects the starter.

The housing of the armatures in a common magnet frame and the connections between the phase advancer slip-rings and starter are diagrammatically indicated in Fig. 17. For star coupling the brushes $a_1$ $b_1$ $c_1$ are joined together and the brushes a b c are connected to the slip-rings. For mesh coupling the brushes $a_1$ and b are connected to slip-ring C; $b_1$ and c to slip-ring A, and $c_1$ and a to slip-ring B. If the phase-advancing is only carried to about unity, but does not make $\phi$ negative, there is no appreciable increase in rotor current, so that there is no increase in rotor copper loss; there is, however, an appreciable reduction in stator current and therefore a saving in stator copper loss. For the same total copper heat the permanent rating of the motor may therefore be slightly increased. Where the rating is fixed with regard to short-time overloads. the increase in rating may be considerable (20 to 30 per cent), so that the cost of a motor with phase advancer will not appreciably exceed that of a larger motor without phase advancer.

The power lost in the phase advancer is very small and is approximately compensated by the saving in stator copper loss, as will be seen from the following figures for which the author is indebted to the General Electric Co.

| B.H.P. of motor | 350 | 375 | 800 |
|---|---|---|---|
| Loss in phase advancer including excitation, watts | 2 000 | 3 740 | 3 900 |
| Saving in primary copper loss, watts | 1 900 | 4 600 | 4 400 |

## METERS AND TARIFFS.

More than 10 years ago Professor Arno, of Milan, invented a meter which takes account of power factor in the following way. The meter registers on the same dial two-thirds of the true energy plus one-third of the kVA-hours. This is achieved in a simple and quite inexpensive way by adjusting the angular setting of the pressure coil.[*]

The values two-thirds and one-third have been arrived at by investigation of the working conditions of a number of Italian supply companies and may, on the whole, have correctly represented the economic conditions of the Italian hydro-electric undertakings. It is, however, not *a priori* certain that it would also be correct for English electricity works. At any rate this system of metering has not found favour in this country. Possibly, also the fact that the consumer could not read off on this meter what was actually the energy for which he had to pay was a drawback. Both these disadvantages have been overcome of late years by a further development of the Arno principle which will be described later.

In this country two methods of charging have been employed. One is known under the name of the "Midland tariff." Under this, the charge for energy consists of two parts, namely, a fixed amount per maximum demand for kVA or current taken at any time during a month or a quarter, plus a flat rate per unit for the energy actually consumed. This requires the provision alongside of the ordinary cosine meter of a maximum-demand indicator which must be so constructed that only a demand sustained over a reasonable time can influence it, as it would clearly be unfair to penalize the consumer for an accidental short-circuit. The advantage of this system is that the consumer can read for himself on the energy meter what amount under the flat rate he will have to pay, and on the maximum demand indicator what the fixed charge per kVA will total up to.

Under the other system, also, two meters are used. One reads true energy, namely

$$\int_0^t \text{kVA} \cos \phi dt = A$$

and the other reads

$$\int_0^t \text{kVA} \sin \phi dt = B$$

From these two readings the average energy factor is found by the equation

$$\cos \phi = \frac{A}{\sqrt{(A^2 + B^2)}}$$

and the charge is made out for a flat rate and for the quantity

$$Q = A \frac{\cos \phi_0}{\cos \phi},$$

which is obviously nothing else than total kVA-hours multiplied by $\cos \phi_0$. Since $\cos \phi_0$, the lowest permissible power factor prescribed by the company, is a constant, the company simply charges at a flat rate for the number of kVA-hours or, if the voltage may be considered constant, for coulombs. In both tariffs the usual coal clause and discount to large consumers can be embodied.

A method not quite as simple as Arno's, inasmuch as it requires two meters instead of one, is in use by some supply companies in France. Arno's meter integrates and shows on one dial two-thirds of the real power and one-third of the kVA-hours. In the French method one meter shows the real energy and the other the reactive energy or $\int$ kVA sin $\phi dt$. The account is made up on a flat rate on the sum of the units registered on the cosine meter plus a certain fraction of the units shown on the sine meter. Here also, as in the case of the Midland tariff, the customer can by inspecting his meters find out for himself not only what is the actual amount of energy he has used, but also what he has to pay for it. The meters are made by the Compagnie pour la Fabrication des Compteurs of Paris in a great variety of types and comprise also a special type, having three dials, for large consumers. On one dial is shown the actual energy, on the other the reactive energy, and on the third the sum of the real and a fraction of the reactive energy. The exact value of this fraction is agreed beforehand between the supply company and the consumer according to the character of his installation, and is provided for by the selection of suitable gearing.

---

[*] *Journal I.E.E.*, 1913, vol. 51, p. 270.

*Messrs. Aron Electricity Meter, Ltd.*, manufacture the Hill-Shotter maximum-demand kVA indicator for use in conjunction with the ordinary cosine meter. Since the plant capacity from the generator to the consumer's terminals is dependent on the current irrespective of pressure and frequency, the instrument is made to register simply the maximum current sustained during a certain time-interval, although the dial is marked in kVA corresponding to the declared pressure. The demand indicator is arranged on the Merz principle, the releasing mechanism being tripped at regular time-intervals by an automatic clock mechanism which is worked by a shunt circuit off the supply leads. The time element is housed in the same case as the meter proper and, since the working agent is merely current, the indication is correct for any frequency.* For balanced loads the instrument may be used in one phase only, but in cases where the supply given to unbalanced loads has to be metered a special three-phase type is made. In such cases the maximum demand does not occur in all phases at the same time, and the sum of these maxima must exceed the true simultaneous maximum. The supply company, however, has to provide plant capacity in each phase corresponding to its individual maximum and not for the simultaneous maximum loading in all the phases combined. If with a balanced load 300 amperes were the combined maximum demand, it would obviously be inadmissible to allow 150 amperes on each of two cables and zero on the third. In such a case of serious unbalancing the use of three maximum-demand indicators is justified. For only moderately unbalanced loads the makers recommend a combined polyphase indicator containing three separate current elements, and this indicator is accurate provided the unbalancing is such that at times of maximum load the current in any one phase does not differ from the mean value of the currents in the other two phases by more than 50 per cent of that mean value.

*Messrs. Chamberlain and Hookham, Ltd.*, have recently developed minimum and maximum energy factor indicators which require no time mechanism. The minimum instrument consists of an ordinary cosine meter and a sine meter having, in addition to the usual pointer, an indicator. The cosine meter has a contact-making device which comes into action after a predetermined amount of energy has passed through the meter. In the sine meter is an electromagnet which, when energized, releases the gear and allows the pointer to return to zero under the action of a spring, the indicator remaining at its then position. Suppose the contact has been set for 10 units. Every time this amount of energy has passed the sine meter returns to zero and, since the lower the energy factor the further will the indicator be pushed, its extreme position corresponds to the minimum energy factor which has occurred during a given period. The dial of the sine meter may be marked either in kVA-hours or directly in cos $\phi$. To record the highest energy factor occurring in a given time the contact device is put into the sine meter and the cos $\phi$ indicator into the cosine meter.

In order to ascertain the general trend in the supply industry as regards discriminative tariffs, the author has made inquiries of some of the larger power companies with the following results. On the whole the importance of framing the tariff so as to induce consumers to take their supply under a good power factor is recognized, but the question is (owing to the unsettled industrial condition) still in a state of flux. Thus one company writes that previous to the war they charged £1 per quarter per kVA of maximum demand plus a flat rate of 0·25d. per unit, but that owing to the increase in prices they had to advance their charges and, everything being so uncertain, they prefer not to state any definite figures.

Another company writes with respect to tariff adjustments according to power factor: "It will be inopportune for you to refer in your paper to the figures we gave you last year, having regard to the possibility of it now being found necessary to amend them."

The engineer of a third undertaking, who wishes to remain anonymous, though he permits the author to mention figures, explains that he uses two cosine meters, one with the pressure phase reversed, so as to get not the sum, but the difference in the two-wattmeter system. From the two readings he finds tan $\phi$ and from this cos $\phi$. The units shown on the true energy meter are increased in the ratio $0 \cdot 8/\cos\phi$, and half this increase is charged in addition to the true units.

*South Wales Electrical Power Distribution Co.*—This company charges on the basis of the following figures per maximum kVA demand (reduced from true energy by dividing by the energy factor) plus a flat rate of 0·25d. per unit.

For the first 500 maximum hourly units per month, 7s. 6d. each.
For the next 1 500 maximum hourly units per month, 6s. each.
For all further hourly units per month, 5s. each.

It is convenient to put this tariff into mathematical form. Let $D$ be the maximum demand in units, $d$ the flat rate per unit, $U$ the units of true energy consumed in one month, and $\cos\phi$ the energy factor. Then the monthly charge in pence is:

---

* See correction to this sentence in the remarks of Mr. E. W. Hill, page 115.—M. W.

For $D$ up to 500,

$$\text{Pence} = \frac{1}{\cos\phi}\left\{aD\right\} + dU$$

For $D$ between 500 and 2 000,

$$\text{Pence} = \frac{1}{\cos\phi}\left\{a\,500 + a_1(D-500)\right\} + dU$$

For $D$ over 2 000,

$$\text{Pence} = \frac{1}{\cos\phi}\left\{a\,500 + a_1\,1\,500 + a_2(D-2\,000)\right\} + dU$$

$$a = 90,\ a_1 = 72,\ a_2 = 60.$$

The *North Wales Power and Traction Co.* write: "Our standard price at present (March 1922) is £6 per kW of maximum demand plus ¾d. per unit; and in the case of bulk supply we specify in the power agreements that the power factor shall be kept as near unity as possible. With industrial works supply we specify that the power factor shall not be less than 0·85, and secondary equipment is installed to our reasonable satisfaction, so that we can take exception to any plant which gives poor power factor."

The *Yorkshire Electric Power Company* write: "Our tariff for power supply is made up of two parts: (1) A charge per kVA of maximum demand. (2) A charge per unit. This tariff definitely encourages the consumer to have regard to the power factor of his installation, and in a number of cases consumers find it economical to introduce special means for improving the power factor of their installations."

The *Scottish Central Electric Power Company* write: "This company has not so far introduced a tariff to induce consumers so to arrange their plant as to provide a good power factor. We have the usual 'Penalty Clause' in respect of low power factor in our agreements for supply, but, owing to the difficulty of enforcing this, it is rarely brought into operation."

The *City of Sheffield* has a tariff * for power based on a fixed charge per maximum demand in kVA and, in addition, a flat rate per unit, with discounts varying according to quantity. The rates originally published in 1913 have now been doubled, and the charges made to large consumers taking a high-tension supply in bulk for any purpose required amount at present (March 1922) to a fixed charge of £8 per annum of maximum demand in kVA and a flat rate of 2d. per unit, less a discount of 75 per cent. The rate is subject to the signing of an agreement embodying a clause adjusting the discount according to the price of coal, also a minimum payment per annum and a term of years.

The *Calcutta Electric Supply Corporation* limits consumers to a power factor of 0·8, and the consumer obtains a bonus if his power factor is better than 0·85. The bonus is in the form of a rebate for each 1 per cent by which the power factor exceeds 85 per cent.

The *Clyde Valley Electric Power Co.* have given the author the following particulars about power factor and tariff, with permission to embody them in this paper: "The mean power factor of our system averages about 0·72 over a week, ranging from about 0·55 to 0·82 daily. We estimate that the increased loss in our 11 000-volt distribution system due to the difference between unity power factor and the power factor obtained is 3½ per cent. The increased loss in transformers and generating plant we put at 0·6 per cent and 0·75 per cent respectively, or a total increased loss of 4·85 per cent. To this must be added the increased steam losses consequent on running additional turbo plant to deal purely with the kVA demand. A further direction in which we estimate that we suffer considerable loss in revenue is the impaired voltage regulation at the customer's terminals due to the lower power factor. The company, therefore, some time ago decided to insert a Power Factor Clause in the standard rates. After careful consideration a 'standard power factor' of 0·8 lag was adopted. The present standard rates are:

"0–250 kW of maximum demand: £10 per annum, plus a running charge of 0·4d. per kWh consumed with coal at 20s. per ton.

"1 000 kW of maximum demand: £8 per annum, plus a running charge of 0·4d. per kWh consumed with coal at 20s. per ton.

"10 000 kW of maximum demand: £6 per annum, plus a running charge of 0·4d. per kWh consumed with coal at 20s. per ton.

"And *pro rata* for intermediate quantities.

"The power-factor rebate is given on the maximum-demand charge, the running charge of 0·4d. being unaffected. With a standard power factor of 0·8 the rebate obtainable with unity power factor is 20 per cent. With a power factor of 0·6 lagging, the penalty becomes 33⅓ per cent, in addition to the maximum-demand charge. In the case of a customer with a maximum demand of 1 000 kW, the rate per kW at unity power factor would be £6 8s.; and with 0·6 lagging power factor it would be £10 13s. 4d., the running charge of 0·4d. per unit being additional in both cases. The rebate is given up to unity power factor, and no allowance is made for power factors on the leading side, these being treated on the same basis as unity power factor. We have given careful consideration to the question of metering the power factor, and the system which we consider introduces fewest difficulties in our Accounts Department is the method of registering the wattless component. The metering of power is accomplished by the three-wattmeter method, and to measure the wattless component only requires the addition of one further wattmeter, which does not in any way interfere with the ordinary metering. We arrange the connections of this wattmeter so that the reading is forward for lagging and the reverse for leading power factor. The wattless component and the kilowatt meters are read at the end of each quarter, and the power factor is determined from the relation of the respective readings. Our Mr. McColl has designed a slide rule with which the power factor can be readily determined by any non-technical person. The method of power-factor metering which we have adopted gives the consumer the advantage of off-time phase-advancing; that is to say, where static condensers are employed these may be left in circuit continuously, and the wattless component which has been registered on the lag side may be cancelled during off hours by the leading current of the condensers."

---

* See correction to this paragraph in the remarks of Mr. S. E. Fedden, page 114.—M. W.

The examples of tariffs cited show that the tendency in the supply industry is rather in the direction of a fixed charge for the maximum demand, augmented by a flat rate per unit, than only a flat rate adjusted according to power factor. The latter is unscientific and can, under circumstances, be unfair to either the consumer or the company, as can easily be seen if we consider two cases which may well arise in practice.

Assume that a consumer installs only synchronous induction motors. His power factor will always be leading, and on a flat rate based on and proportional to $\cos \phi_0/\cos \phi$ he will always pay too much. Yet as long as his neighbours have a lagging power factor he is benefiting the supply company. Only in the unlikely case that all consumers were to use the whole supply to work phase-advancing motors would the company also be injuriously affected.

On the other hand, a consumer may use ordinary motors and correct the general power factor of his whole installation by static condensers. With a load factor of 0·83 he will consume, every working day of 8 hours, 660 units for every 100 kW of his peak load. Under a tariff which allows him an energy factor of 0·85 without penalty he will be able to make the necessary correction by installing condensers, but he will not install more than are absolutely necessary. His mean load is 0·83 of the peak load, and his power factor at peak load may be as low as 0·7. Taking this as a reasonable figure, we find that at peak time his condensers will have to inject 39 kVA for every 100 kW of peak load. If he leaves the condensers in circuit for 24 hours a day he can reduce their capacity to one-third and yet keep within the permissible power factor of 0·85. But at peak time his power factor will be only 0·78, and as the intention of the tariff is to make the consumer pay his fair share of the additional current load on the plant at peak time, he ought to pay 0·85/0·78 = 1·11 times the minimum rate. Actually he only pays the minimum rate. The company receives 11 per cent less than corresponds to the intention of the tariff.

Such anomalies cannot occur under a maximum-demand tariff. The consumer may leave his condensers in circuit permanently without depriving the company of a certain percentage of the revenue to which they are entitled, because the fixed charge is not influenced, or is only slightly influenced, by energy factor. For the same reason the consumer cannot be penalized for doing a little more phase-advancing than is necessary. The basic idea of the two-part tariff is that the fixed charge for maximum demand should recompense the company for capital outlay incurred on account of each consumer, whilst the flat rate per unit should recompense them for running costs. If the voltage at consumers' terminals is kept constant, the maximum kVA demand can be found from a maximum-current indicator scaled in kVA. Under these conditions the metering becomes a very simple matter. All that is wanted is a coulomb meter combined with a time element which brings the pointer back at regular intervals of 10 or 20 minutes, leaving the indicator in its farthest position, and an ordinary cosine energy meter. Neither energy factor nor power factor enter in the making up of the total charge, and the customer can by inspection of the two meters find out for himself what energy he has used during a month or a quarter and how much he has to pay for it. This is an advantage, especially with small consumers, who cannot be expected to understand the mathematics of power and energy factor.

The condition of constant terminal voltage may not, however, be strictly maintained. If the voltage is higher than the declared voltage on which the maximum demand indicator is scaled, the number of kVA read off the indicator, and also the fixed charge, will be too low, to the detriment of the supply company. If the terminal voltage decreases, the indicator will show too large a value for the maximum kVA, to the detriment of the consumer. The greatest voltage-drop occurs at peak time and, generally speaking, this is the time when consumers individually have their own peak demand. The result is that the fixed charge will be in excess of that for the true maximum kVA demand in the same percentage as the actual voltage falls short of the declared voltage.

The error thus introduced by excessive voltage-drop may be appreciable and, as it is always against the consumer, we find that most supply companies do not use the simple (coulombs)/(time) indicator, but replace it by a (units)/(time) indicator, and translate the reading into maximum kVA demand with reference to the energy factor by dividing the number of units by $\cos \phi$. Under this more accurate system of metering three instruments are required: (1) A maximum-demand kW indicator which is a cosine meter with a time element; (2) an ordinary cosine energy meter; and (3) a sine meter to record $\int EI \sin \phi dt$. From the two last-named instruments is found $\tan \phi$, and from this $\cos \phi$.

If $P_0$ = maximum kW demand,
$P$ = maximum kVA demand,
$m$ = charge per maximum kVA demand,
$U$ = number of units consumed,
$d$ = flat rate, then

$$P = \frac{P_0}{\cos \phi}; \text{ and the total charge } = mP + dU$$

Under this tariff there is no necessity to place the consumer under any restriction as to a minimum power factor. The latter may be as bad as suits the consumer's method of working his machinery, because its effect will make itself felt in the energy factor and thus appropriately increase the fixed charge, thereby recompensing the supply company for their greater expenditure on electrical plant.

In conclusion the author thanks the various firms and engineers of power supply undertakings for the information which they have kindly supplied to enable him to present this paper.

## Discussion before The Institution, 16 November, 1922.

**Mr. Ll. B. Atkinson :** The circumstances in which this paper is read to-night are most unusual. The paper was presented to the Institution in April of the present year, and four months later the author had died. We are deeply indebted to Prof. Miles Walker for having carried the work to a point which has permitted the reading of the paper to-night. Gisbert Kapp was one of my earliest and most intimate friends in the electrical world. The last time I saw him was during my tenure of office as President of the Institution, when I spent a night with him at his home at Birmingham. We had been to an Institution meeting, and, when we got home, his family and household had retired to bed. He said to me: "Atkinson, we must have a night like we used to do, and a long discussion." It was then about half-past ten. The discussion continued until between two and three in the morning, just as in the days when we were young men we would spend half the night discussing many of the difficult problems which confronted us in those days. To me, and I am sure to him also, it was a great delight thus to revive a form of entertainment and instruction in which we had so often taken part in our young days. I realized at that time that he was failing physically very fast, but he was mentally—as this paper shows—as alert as ever. It is difficult for me—and there are one or two members present who will recollect those early times—to realize how, when Kapp began his work on the dynamo and other electrical subjects, he and all of us were groping in the dark. I saw, in those evenings I spent with him, how step by step he was coming to the idea of the magnetic circuit, which finally unlocked so much. I believe the brothers Hopkinson published the same idea before he did, though not in the same terms, but nevertheless Kapp was working on the idea before anyone else in the electrical world had got a grip of the fact that we could use the idea of a circuit for magnetic actions in the same way as we had been accustomed to use the idea of an electrical circuit. That method, in fact, was a revolution. After that Kapp went on, always as a leader—at one time he was our President—and as a teacher. The transmission of power, alternating currents and many other matters in turn claimed his attention, always with some new illumination which he communicated to others freely, in teaching, in papers and in books, and now to-night, after he has gone, we still hear his voice and sit once more as learners at his feet.

**Dr. S. P. Smith :** The paper brings out to a certain extent the point that power factor improvement is not merely an economic question at the present time, but is becoming a question of necessity on certain systems in order to obtain a good voltage regulation. The question of the particular apparatus which ought to be used is, of course, no new one. We are greatly indebted to Dr. Kapp, however, for giving us such a valuable criticism of all the useful methods that are known at the present time. In this connection I should like to refer to two papers * published in 1909. It is interesting to note that Prof. Miles Walker, who has been so good as to revise Dr. Kapp's paper, was also a pioneer in this matter. In Mr. Mordey's paper, the conclusion arrived at in comparing static with rotary condensers at that time would seem to be confirmed to a large extent by the present paper; both as regards capital cost and running cost, Mr. Mordey found that the rotary was more expensive than the static condenser. It is well known that in many systems the static condenser is being used as a protective device, and it may well be that in some installations the static condenser can be used to serve both for protection and for improving the power factor, though the possible injurious effect of capacity where there are voltage ripples must not be ignored. One point in connection with the synchronous induction motor came out in a discussion which I had with Dr. Kapp, i.e. its low overload capacity. The synchronous induction motor is a compromise, the synchronous motor being a machine with small armature reaction, and the induction motor a machine with large armature reaction; combining the two results in a small overload capacity, which may be troublesome in some cases and need special design to overcome it. In conclusion, I should like to refer to the final part of the paper, dealing with tariffs. The author has given us several methods of charging.

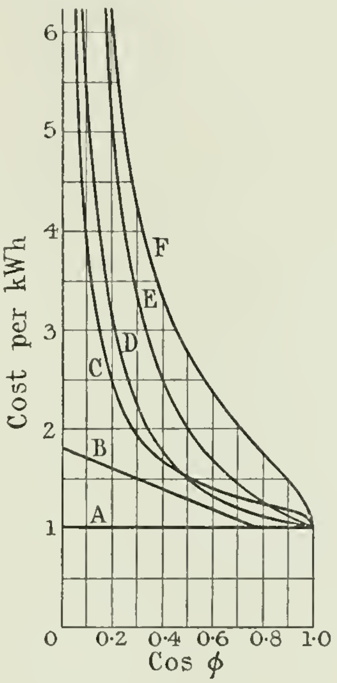


Fig. A.

---

* W. M. Mordey: "Some Tests and Uses of Condensers," *Journal I.E.E.*, 1909, vol. 43, p. 618.

M. Walker: "The Improvement of Power Factor in Alternating-current Systems, *ibid.*, vol. 42, p. 599.

Fig. A is taken from a publication * of the Swiss Electrotechnical Institution, and shows at a glance the effect of different methods of charging.

Let power component $\int VI \cos \phi \, dt = X$,
reactive component $\int VI \sin \phi \, dt = Y$,
total kVA-hours $\int VI \, dt = Z$.

Then curve A = charge according to $X$,
C = charge according to $X + 0 \cdot 3Y$,
D = charge according to $0 \cdot 5X + 0 \cdot 5Z$,
E = charge according to $Z$,
F = charge according to $X + Y$.

In general, the charge may be proportional to $(1 - a) X + aZ$, since the generating cost depends on $X$, and the transformation and distribution costs are proportional to $Z$. Curve E thus represents the case when the generating costs are negligible compared with the transformation and distribution costs, while curve A represents the case where the only important cost is that of generation. The value of $a$ must obviously be adjusted to suit given conditions. In hydro-electric work $a$ would obviously be very different from its value with a steam generating station. Curve B shows how the cost can be increased by 1 per cent for each 1 per cent reduction in power factor below 0·8.

**Mr. K. Edgcumbe:** On the last page of the paper the author gives it as his opinion that the correct charge is an amount per kilowatt-hour plus a fixed charge depending on the maximum demand, and he lays it down that this fixed charge should recompense the company for the capital outlay incurred on account of that consumer. This, I think, is the aim of every supply undertaking. He goes on to point out that if the voltage can be regarded as constant, all that is necessary is a coulomb meter combined with a time element or, in other words, an ammeter with a maximum-demand pointer, and that is undoubtedly the simplest method. The author, however, qualifies that statement by adding that the condition of constant terminal voltage may not always be fulfilled. But I am inclined to think that the alternative given by the author is subject to another objection almost as strong and, apart from this, it is complicated, entailing three instruments: the ordinary cosine (energy) meter, a maximum-demand indicator and a sine meter. By taking the readings of the sine meter and the energy meter, and dividing one by the other, the tangent of the angle can be found; from that, in turn, the angle and hence the power factor can be calculated and the kilowatts may be read from the maximum-demand indicator. By dividing the one by the other, the maximum demand in kVA is obtained. Now this appears to me to be a very elaborate way of arriving at the result, and it is subject to the objection that the power factor measured is the *average* power factor for the quarter. I do not think that one is justified in assuming that it was the consumer's power factor at the time he was taking his maximum demand. Comparing the two systems, therefore: in the one case there is the possibility of the voltage varying (in favour of either the consumer or the supply company), and in the other case there is the certainty that the power factor assumed is not the power factor at the time of the consumer's maximum demand. Of the two alternatives I prefer the former. The strong point in favour of that method is that it embodies a maximum-demand ammeter which is at all times easily seen by the consumer; whereas in the other case he cannot tell until the end of the quarter what his maximum demand has been, and then it has to be multiplied by a constant, the object of which is difficult to explain, and the method of arriving at which is complicated.

**Mr. W. E. Rogers:** When one first studies the power-factor-improvement problem, everything seems to point towards the employment of static condensers, until one realizes that the voltage question has an important bearing on the matter, and that unless about 600 volts can be applied to the condensers they will not be a practical commercial proposition. Moreover, the question of master patents arises. I should like to have some information in regard to the power factor of a.c. electric arc furnaces, and a.c. electric arc welding processes, etc. With ammeter, wattmeter and voltmeter readings a power factor of the order of 0·4 or 0·5 is indicated. It seems to me that there is a total absence of current during a certain portion of a cycle, and there is therefore no wattless current to correct. How is that power factor produced (if it is a power factor), and how is it to be improved? Would not "equivalent power factor" be a more appropriate expression?

**Mr. E. T. Williams:** I had occasion to consider this subject recently in connection with a works where the power factor was gradually becoming worse. The old agreement with the supply company was on the kilowatt basis; the main was being overloaded and there were voltage troubles. We therefore had to face the problem, particularly as the supply company in their new agreement were charging on the kilovolt-ampere basis. After considering the various methods of dealing with the problem we installed a static condenser and, after testing it, found it to be a commercial proposition. From that time until the present we have not had the slightest trouble with it. I cannot but feel that all old agreements made on a kilowatt basis should be replaced, as they expire, by new agreements on a kilovolt-ampere basis. I also feel that in many cases where extensions or enlargements of mains appear to be required, the trouble might be overcome by providing some type of phase advancer. The great advantage of the static condenser is that one merely has to put it into position; it requires no attention, and is advantageous from the points of view of both the consumer and the supply company.

**Mr. W. B. Woodhouse:** I think it is some 18 years since I first adopted a method of charging based on kilovolt-amperes, with the object of dealing with this question of idle current. The paper gives us some idea of the relative merits of the different means of correction, but the problem we have to face in practice is: Who shall do the correction, the supply undertaking or the consumer? Of course, if supply engineers could design all the installations, then motors would be obtained with less magnetizing current than most of them now require, and we could in every way reduce the amount of idle current on the system. As that is not possible, the user has to be encouraged to improve his power factor by a tariff. I do not think it is really necessary for that tariff to follow the cost line too precisely. A consumer should be prohibited from having a power factor of the order of 0·5 or 0·6. That can be done by imposing regulations, but it should be made prohibitive in price for anybody to have an installation with so low a power factor. That can be effected by a fairly high kVA charge. I have dealt with a number of cases where the consumer has corrected the power factor and reduced the demand very substantially. I have found synchronous motors very convenient for a number of purposes where there is continuously-running machinery. I installed one 10 years ago which is still running, and which has an automatic pressure regulator. This regulator is actually designed to regulate the pressure, but it also regulates the power factor. I believe that the installation of that particular machine, as compared with an induction motor, saves the consumer something like £2 000 a year. In another case, a very large installation—one of those difficult installations in which there is a large number of heavy motors to meet peak conditions—was working with a power factor of something like 0·5. That has been corrected by means of static condensers, with the result that the bill for current has been reduced by about £8 000 a year.

---

* O. GANGUILLET: *Schweizerischer Elektrotechnischer Verein Bulletin*, 1921, vol. 12, p. 406.

**Mr. C. L. Lipman:** I agree with the author that a fair way of charging for electricity consumed, from both the consumer's and the supply company's point of view, is to have a fixed charge for the maximum demand, augmented by a flat rate per unit. In the last chapter the author repeatedly refers to the integrating wattmeter or watt-hour meter as the "cosine meter." This name may be justified from the time-integral point of view, but is objectionable for other reasons. On the Continent by a "cosine meter" is usually meant a power factor meter and not an energy meter. It is further surprising that in a paper dealing with the "Improvement of Power Factor" no mention is made of power factor indicators. Wherever power factor regulation is attempted a direct-reading power factor meter is necessary, as it is out of the question to calculate the power factor from the readings of wattmeters, voltmeters and ammeters. It is a well-known fact, and reference to Figs. 7 and 9*b* of the paper will confirm it, that in the case of synchronous machinery the power factor varies with the load on the machine. It is therefore of extreme importance to employ such a power factor meter as would indicate the exact power factor or phase angle between the current and the electromotive force, independent of the magnitude of these quantities. Such an improved power factor meter has recently been developed by the speaker and possesses many novel and unique features. It works on the principle of the "component fields," according to which the electromagnetic forces acting upon the moving-iron system are produced by field coils having their axes parallel to each other in separate parallel planes, the moving element comprising a spindle (made up of one or more co-axial magnetic systems, which are being magnetized by individual pressure coils) and an appropriate number of thin iron vanes mounted thereon in these parallel planes. The vanes are specially shaped, and their axes of symmetry are set so as to correspond to the time-electrical displacement (expressed in degrees of phase angle) of the currents in the various phases of the system on which the instrument is to be used, i.e. 90° and 120° for two- and three-phase circuits, respectively. The distinguishing feature of these phase meters is that, owing to their special construction, no resultant rotating field is set up, and consequently no "rotational drag torque" upon the moving-iron system is produced, and the disadvantages arising from that torque are eliminated. The magnetic fluxes due to the current coils always oscillate to and fro periodically in parallel planes. The fluxes due to the pressure coils oscillate periodically up and down co-axially, thereby magnetizing the corresponding iron vanes of the independent, but component, magnetic portions of the moving systems, these portions being magnetically separated by non-magnetic material. The turning moment on the moving system is therefore developed by virtue of the fact that a number of directive pulsating magnetic forces, due to the field coils, are regularly applied to the vanes magnetized periodically and in correct sequence by the pressure coils, which vanes may be regarded as magnetic levers mechanically displaced relatively to each other. The combined electromagnetic effect is such that for any given power factor the moving system is in neutral equilibrium, and thus it is independent of the magnitude of the load. If the phase angle between the current and potential difference of the mains alters by a given amount, the moving system will shift by an equal amount, and will again take up a definite and stable position corresponding to the new conditions. The position of the pointer therefore indicates the phase angle. For convenience, however, the scale is graduated in values of the power factor.

**Mr. W. M. Selvey:** I should like to separate, to some extent, technical questions from the question as it appears to consumers. It is undoubtedly a fact, from the technical point of view, that the magnetizing current should be provided at the place where it is wanted, and that it should not be transmitted by the supply undertaking. Hence we are now adopting the practice of using a sine meter at a consumer's terminals for integrating the total amount of magnetization. For a number of years I have been using cosine meters reversed as sine meters for the accurate determination of power factor on steady load. In connection with a commerical load, however, the matter must be regarded from a rather different aspect. There are two separate factors to be considered, the capital expenditure on mains and generating plant, and voltage regulation. The sine meter measures or adds up wattless units or, as Mr. Woodhouse called it, idle current. Thus it may be used to measure the magnetizing kVA taken by all the motors over the whole system. It cannot be applied, for instance, to show the power factor at the time of maximum demand, for a very much lower figure will be indicated as the average power factor. The maximum-demand indicator measures only the power factor at the period of highest load, and therefore deals with the capital charges part, which the sine meter does not. Either of these methods separately, therefore, would not sufficiently disclose to us the relative cost of giving a supply to any particular consumer; we want both of them. Surely that is the only reason for studying the subject. We make the supply as cheap as we can and, as far as tariff is concerned, we try to be fair as between one consumer and another, and all metering is dictated by this desire. It is very difficult to explain to the non-technical customer what power factor really is, and why he should be charged more or charged less under different circumstances. It is undesirable to lay too great stress upon it unless the supply undertaking is so well convinced of the value of any improvement to them that it is prepared to give a rebate on the price. In doing that, they are trying to be as fair as possible to the consumer who is prepared to help them to cheapen the supply. The other point of view, which has been voiced by Mr. Woodhouse, is also in my opinion correct in the sense that, if a consumer has a really bad power factor, I think one is entitled to say to him: "You are abusing your privileges, and we shall simply not allow it at any price." In some such cases where I have had to act for the consumer and advise him as to the way in which he should satisfy the requirements of the supply undertaking, I have told him frankly: "I cannot contend on your behalf that running with a very low power factor is fair to the supply undertaking or to the other consumers." He has been impressed by this argument and I have had no difficulty at all in converting, with the help of the manufacturers, large induction motors running at a very bad power factor into synchronous motors by the injection of direct current into the rotor. I think that is the best way of dealing with the problem, but I rather deprecate any very strong pressure being put on individual consumers, because we are only now gradually developing these synchronous motors to any large extent. In this connection perhaps it would be interesting if Prof. Miles Walker would consider a small point which is not quite clear to me at present. Take one of these motors having a synchronous stalling torque somewhere about full load. There is a certain point, subject to the amount of excitation used and to the air-gap, where it is unstable. Electrical and mechanical engineers sometimes have to use a reciprocating machine where, under certain conditions, there is a very large cyclic irregularity. What will happen if we put two or three of these motors in parallel under conditions of considerable cyclic irregularity, where the load on each is constantly liable to be on the unstable part of the curve?

**Mr. W. E. M. Ayres**: There is one matter which I know the author intended to add to the paper, i.e. the possibility of improving the power factor by re-grouping the motors. There has been much discussion in the United States on power factor improvement, and in these discussions the re-grouping of motors is always given as the first method of tackling the problem. Of course, that cannot always be done; there are certain circumstances in which individual drive is absolutely essential. Unfortunately, in many of these cases of individual drive there is bound to be a very low load factor, e.g. rubber works, bleaching works, etc. At the same time, a very great improvement may be effected by the re-grouping of motors. I think that is one of the reasons why the individual driving of looms in textile mills is not so popular as it once promised to be; the little motors employed must have an extremely high starting torque and even at full load a power factor of only 0·77 or 0·78, but running, as they normally do, at $\frac{2}{3}$ full load, the power factor is reduced to 0·6. By driving the looms in groups or rows, with underground high-speed shafting running in roller bearings and with upward driving—which is quite easy to arrange—all the advantages of individual drive can be obtained, but the diversity factor will correct that difference in output required between normal load and working load, and the power factor will be greatly improved. There is little doubt that in the future very large extensions of industrial load will be employed, and the proper utilization of synchronous motors will ensure a reasonable power factor under such conditions. At the same time, there will be trouble in an industrial district like Birmingham where there are hundreds of small works using only one or two motors of 5, 10 or 15 h.p., probably running at about half load; it is a problem for the supply undertaking to know what to do under such conditions. One cannot insist on all these consumers putting static condensers on their motors. At the same time, the increased bulk supply will very largely correct the power factor on the feeders. I have had a good deal of experience of the induction-type synchronous motor, which seems to have given excellent results. The experimental work in connection with them was done a long time ago; I believe Danielson's patents date back to 1900. It is only during the past few years, however, that they have come into their own. They are now being widely adopted, and, although they have been criticized, I believe they have never been actually condemned. Although it does not refer to the motors made by the firm with which I am connected, the point has been raised as to whether a certain amount of trouble is not experienced with the exciter drives on these motors. With the salient-pole type of synchronous motor the field winding is screened by the damping winding in the pole-shoes, but with the induction-type synchronous motor the field winding is not screened. Any pole-swinging due to a change of load will cause circulating currents which, in the induction-type synchronous motor, must pass through the exciter, thus creating very large torques in the exciter. Those torques, in extreme cases, might amount to as much as 10 times the normal exciter torque. I believe that in some cases trouble has resulted because that point has been completely overlooked.

(*Communicated*): Much has been made of the small overload capacity of the induction-type synchronous motor, and I am glad to see that the author elaborates my remarks in the discussion of Mr. Carr's paper * by his Figs. 2 and 3. It is a rule, in well-designed motors of this type, to give 75 to 100 per cent overload capacity, and, according to my experience, greater overloads are usually looked after by the circuit breaker. I do not consider that the synchronous motor and the motor with phase advancer are really competitive alternatives. Each has its own sphere of utility and its own limitations. It is not economical to correct power factor much beyond unity with phase advancers, not only on account of the rotor heating, but chiefly on account of the disproportionate increase in size of the phase advancer itself. On the other hand, it is very economical to do quite a large amount of phase correction by means of a few over-excited synchronous motors working at, say, 0·80 leading power factor. For single large motors and where leading kVA at light loads is not required, the phase advancer will score. Where the motor to be corrected is subjected to very heavy overloads, the phase advancer will also prove superior. On the other hand, with a miscellaneous system it is cheaper and more economical to make one or two of the large motors of the synchronous type with leading power factor and constant excitation at all loads. The increased slip when phase advancers are used must not be forgotten if the motors are for driving fans or centrifugal pumps, as these machines are very sensitive to speed variation. Also, the fact should be kept in mind that with induction motors the overload capacity is reduced in proportion to the square of the voltage, whereas with synchronous motors it is reduced in direct proportion only. This may be of considerable importance on some systems with widely varying voltage. There is no appreciable difference in either efficiency or cost between the two methods of power factor correction, and the lower economic limit in each case seems to be for units of 120 to 150 h.p. Attempts have been made to utilize electrolytic capacity in the rotor circuit of induction motors as a phase advancer, but so far this is in an experimental stage, and for scattered systems of small motors there appears to be no alternative to the static condenser at the present time.

---

* *Journal I.E.E.*, 1922, vol. 60, p. 165.

**Professor W. Cramp** (*communicated*): It seems to me very fitting that I should take this opportunity of communicating to the Institution the results of experiments suggested by the late Dr. Kapp, and arising out of his discussion on the paper * by Mr. Carr. Dr. Kapp, at the time of his remarks, declared that if he had been still at the University of Birmingham, he would have made these experiments, so I at once undertook to get them done. They were carried out very satisfactorily by Messrs. Elliott and Francis, who were fourth-year students at the time and are Students of the Institution. In his calculation of the torque at which a synchronous induction motor will synchronize, Mr. Carr omitted the effect of putting the exciter reactance into the rotor circuit. Dr. Kapp insisted that this would materially affect the induction motor torque, and the result proved that he was quite right. For this purpose a Siemens standard three-phase induction motor with a slip-ring rotor was tested with various additional reactances put in the rotor circuit. The ratio of the added reactances to the original rotor reactance varied in the tests from 0 to 8. But, as it was estimated that the ordinary exciter armature would only make this ratio about 0·5, I shall quote the results corresponding as nearly as possible to that figure, namely, to 0·439. The comparison is then as follows: With no additional reactance and a stator current of 34 amperes, which corresponds approximately to full load for the machine, the torque was 64 pound-feet and the output 7·4 kW. With the reactance inserted, and practically the same stator current, the torque was reduced to 57 pound-feet and the output to 6·8 kW. This result will sensibly modify the figures given by Mr. Carr, and also Dr. Kapp's own circle diagrams; and when the switching arrangements are such as to insert the exciter armature at the time of synchronizing, it will render of doubtful value the theoretical calculations put forward by the former. Complete curves were taken over the whole range of output for the motor, but the important result is that corresponding to full load for which the figures are given above.

**Mr. E. W. Dorey** (*communicated*): The static condenser for the improvement of power factor has been adversely criticized by Mr. Rogers on the score that its cost renders it an unsound commercial investment. This statement must have been made without a knowledge of facts, as I have connected on behalf of the manufacturers with whom I am associated numerous installations of static condensers which give the consumer a return varying from 50 to 80 per cent and more per annum on capital outlay, and surely this is a sufficiently sound investment. The static condenser can be connected to a circuit and for all practical purposes forgotten, as it needs no attention, has a high efficiency—not less than 99·5 per cent—has proved itself to be a thoroughly sound investment for the correction of power factor of both individual motors and motors in bulk, and merits the closest consideration on the part of all engineers interested in the improvement of power factor. A static condenser connected direct across the stator terminals of an ordinary induction motor, of either the slip-ring or squirrel-cage type, and switched on or off with the motor, provides a very straightforward and satisfactory means of improving the power factor of an individual motor. According to Dr. Kapp, the synchronous induction motor costs about 20 per cent more than the induction motor of the slip-ring type, and this difference in cost, together with the better efficiency of the induction motor, will in the majority of cases be almost sufficient to pay for the static condenser. An induction motor combined with static condenser would give all the advantages of the induction machine and none of the disadvantages of the synchronous induction motor, as with the latter the synchronous stalling torque is a serious drawback and it is impossible to short-circuit the slip-rings. There is also the maintenance and attendance on the exciter to be considered, and, generally, the synchronous induction motor is a more complicated machine. Dealing with the question of tariffs, it is now becoming generally recognized that a penalty for low power factor is a necessity if the supply undertakings are to have any hold on the consumer. I know of large supply undertakings operating to-day with a power factor of 60 to 70 per cent and they are quite helpless in the matter, as their standard rates do not penalize the consumer for low power factor. If the consumer is penalized for low power factor, the problem resolves itself into a pecuniary one, and the manufacturers of synchronous plant, condensers, etc., may be safely relied upon to solve all the low power-factor problems to the advantage both of consumers and the supply undertaking. Rules and regulations enforcing a limit of power factor cannot be expected to provide a satisfactory solution, as the consumer must be induced and not driven to improve the power factor. The two-part tariff, a fixed charge per kVA per quarter or per annum, with a running charge per unit, has proved to be a sound tariff on several large supply undertakings known to me personally, but the development of this form of tariff is being retarded owing to the difficulty in getting a really sound metering equipment which is not too expensive. For small loads a popular combination is a Reason electrolytic demand indicator and a unit meter, and for larger loads the Hill-Shotter meter referred to by the author gives reasonably satisfactory results, but what is badly needed is a meter which will accurately record the kVA average demand over a time period and over a reasonable range of power factor. I understand that one meter maker at least is busily engaged on the solution of this problem, and there is certainly ample scope for development in this direction. I am not in favour of a combination of cosine meter and sine meter, as with this metering equipment the supply undertaking plays into the hands of the consumer, who might have a static condenser installed, and by connecting it in circuit during no-load hours would reverse the sine meter and so give an entirely fictitious average power factor, which might in fact give a result showing a leading power factor when actually the power factor at time of maximum load was lagging to the extent of 60 per cent or even worse. It appears to me that the chief concern of the supply undertaking should be to ascertain the power factor at time of peak load, i.e. the maximum demand in kVA, and this brings one back to the two-part charge referred to above. As far as electricity supply undertakings are concerned, no rapid development in the employment of apparatus for the improvement of power factor is likely to take place until a penalty for low power factor becomes general, and then some real progress will be made. The application of a two-part tariff of kVA demand and running charge has gone far beyond the experimental stage, and has been proved by many supply undertakings to be a thoroughly sound commercial tariff and one which tends to reduce the average price per unit sold to a minimum by the more efficient utilization of capital expenditure on all plant rated in kVA, such as alternators, cables, transformers, etc., and a decrease in generation and transmission losses.

---

* "Induction-type Synchronous Motors," *Journal I.E.E.*, 1922, vol. 60, p. 165.

**Mr. S. E. Fedden** (*communicated*): The subject of power factor and its correction becomes increasingly important to both supplier and consumer, and any suggestion which will fairly distribute the burden of rectification as between the interested parties must receive the utmost consideration. The causes, effects and rectification of low power factors are exhaustively dealt with in the earlier portion of the paper, and our thanks are due to the author for so lucid an explanation of the methods which may be adopted either to neutralize entirely or, at any rate, minimize the effects of the inherent difficulties. Obviously the particular method of rectification will depend on the individual circumstances connected with each installation, and all appear to have advantages in certain particular instances. I am particularly interested in the section dealing with meters and tariffs. I am not impressed by the Arno method, as it is not a true indicator of any factor connected with the supply. The introduction of the Merz principle in the measurement of kVA by the Hill-Shotter demand indicator is a step forward, but this instrument relies upon a constant voltage for its accuracy. However, I think it is to be preferred to a thermal indicator, to which we have hitherto been restricted when requiring to measure kVA. The examples of the various tariffs in force are extremely interesting, but I should like to make a slight correction in the tariff quoted as in operation at Sheffield. At the time the details were gathered, the increase was 100 per cent on the ordinary flat rate, but such increase did not necessarily apply to the maximum-demand rate, the basis of which is £4 per annum per kVA of maximum demand, plus ¼d. per unit, subject to a coal clause. The confusion is caused by the fact that at one period during the war the maximum-demand consumer was given the option of being charged either according to the coal clause or in accordance with the authorized general percentage increase on the price list. While the price of coal was exceptionally high during the coal strike, the former option was exercised, but when prices for coal fell, the usual rate was restored. Perhaps the most interesting tariff quoted in the paper is that of the Clyde Valley Company, which embodies many novel features. The reasons underlying the differential charge per kVA for varying demands is not apparent, but the adoption of a standard power factor, with rebates or penalties for any variation, appeals to me as being a fair arrangement between consumer and undertaker. I also agree with the limitation of the rebate to power factors up to unity, as of course it is possible for a leading power factor to be as objectionable as a lagging power factor. In the paper it is suggested that four wattmeters are used to record the various measurements, but it appears to me that two instruments only are required, viz. a three-phase cosine meter with maximum-demand attachment and a sine meter to determine the wattless component. Personally, for my own undertaking, with comparatively short transmission lines, I cannot see my way to allow the penalties incurred during the ordinary working hours (when power factor rectification is most advantageous) to be cancelled during " off " hours by leaving condensers continuously in circuit. The objection would particularly apply to week-ends, when the leading component could not be economically or usefully applied. The author goes on to show how this method of charging might result in penalizing the undertaking. In Sheffield the system adopted is to measure the maximum kVA on a thermal indicator, and the power by the ordinary cosine meter. We recognize the possible error due to excessive voltage-drop, and have under consideration the substitution of the method described by the author in the last paragraphs of the paper. From the commercial point of view, the rectification of power factor by the consumer will repay the capital expenditure in about 2 years when the demand charge is £4 per kVA and the cost of static condensers is in the neighbourhood of £5 to £6 per kVA.

**Mr. E. W. Hill** (*communicated*): A slight error appears in the reference to the Hill-Shotter maximum-demand kVA indicator in the section of the paper headed "Meters and Tariffs," where it is stated that the "indication is correct for any frequency." In point of fact, although moderate variations of frequency from the declared value, such as might be expected in practice in a supply system, do not affect the accuracy of this instrument, which is self-compensating for such variations, yet the instrument would require separate calibrations for two frequencies differing widely, e.g. 25 and 50 periods. It is probable that the sentence was intended to read "and since the working agent is merely current, the indication is correct for any *power factor*," which is a correct statement of fact. A very interesting description follows of Messrs. Chamberlain and Hookham's arrangement of energy factor indicators. The arrangement as described, however, invites criticism on one or two points. First, as regards the operation of the instruments arranged to indicate the maximum energy factor, when this factor (I prefer to adopt the more usual term "power factor") has a value in the neighbourhood of unity, the sine meter (which has then the contact-making device for operating the non-return pointer on the cosine meter) will register very slowly, and indeed should not register at all at unity power factor. In this instance the consequence will be that the contact-making device will not operate, and the cosine meter's pointer will be pushed on and on without ever being released, no definite indication will be given, and the non-return pointer mechanism will probably jam the cosine meter's wheelwork. It is evident that the graduations on the non-return pointer scale must become very open towards the upper end, and the important point on the scale, i.e. that for unity power factor, will be missing. In the minimum power factor arrangement, since the cosine meter with the contact-making device will not register at zero power factor, the power factor scale will have similar characteristics, and will be incomplete at the zero power factor end. A difficulty may also arise in dealing with loads occasionally having leading power factors. A sine meter will reverse when the power factor leads, and a non-return pointer device may be very difficult to arrange on a meter which reverses, if one still expects to get the pointer to give an indication. I consider also that the suggested marking of the non-return pointer scale in kVA-hours (as an alternative to cos $\phi$) would be very misleading. The term kVA-hours should plainly be reserved exclusively for the time integral of kVA. Here, however, the meaning of the indication on the scale can only be that so many kVA-hours have passed during the time that, say, 10 energy units have passed; and such an indication, while suggesting a true integration or registration of kVA-hours, really indicates nothing of the sort. At the present time there is a prevalent misapprehension as to the information given by a sine meter's registrations; there is, as a matter of fact, a grave fallacy underlying the employment of a sine meter. In this paper and in other publications it is implied or stated without any qualification that a sine meter used in conjunction with a cosine meter enables the true kVA-hours passed during a given period of time to be calculated. Now this is demonstrably untrue (except in the one exceptional and particular case where the power factor has remained absolutely invariable during the whole time under consideration, in which case, it may be remarked, a sine meter would hardly be necessary at all), and it is extraordinary that such an erroneous idea could be so persistent. Since so-called "average power factors" are calculated from sine and cosine meter combinations, and since in the aggregate large sums of money are paid by consumers on the basis of such calculations, it is well that it should be clearly known what a sine meter does, and does not do. Taking the author's symbols $A$ and $B$ to represent respectively the registrations in a given time of a cosine and a sine meter, it is erroneously assumed that the kVA-hours passed during that time are

$$\sqrt{(A^2 + B^2)}$$

Consider, however, three consecutive periods of time during which the power factor has assumed three successive different values, although it has remained constant during each one of the three periods. Suppose that the cosine meter's registrations for each of the three periods are $A_1$, $A_2$ and $A_3$, and that the sine meter's registrations are $B_1$, $B_2$ and $B_3$. We can then accurately state that the true kVA-hours for each period are respectively $\sqrt{(A_1^2 + B_1^2)}$, $\sqrt{(A_2^2 + B_2^2)}$, $\sqrt{(A_3^2 + B_3^2)}$ and that the true total kVA-hours for the whole period are

$$\sqrt{(A_1^2 + B_1^2)} + \sqrt{(A_2^2 + B_2^2)} + \sqrt{(A_3^2 + B_3^2)} \quad . \quad (1)$$

Now according to the fallacious assumption referred to above, taking the total registration on the cosine meter to be $(A_1 + A_2 + A_3)$ and on the sine meter to be $(B_1 + B_2 + B_3)$, the total kVA-hours would be calculated as

$$\sqrt{\left\{(A_1 + A_2 + A_3)^2 + (B_1 + B_2 + B_3)^2\right\}} \quad . \quad (2)$$

It is quite plain, however, that expressions (1) and (2) are not, in general, equal; and it can be proved that (2) is always less than (1) (except in the particular case when $A_1/B_1 = A_2/B_2 = A_3/B_3$). A few arithmetical examples would make the matter quite obvious. In other words, the calculations from a sine and cosine meter combination used over a period during which the power factor has varied, always give a quantity which is less than the true kVA-hours. The defect from the true value is the greater the more the power factor has varied, and may be very considerable, e.g.

as much as 30 per cent in some extreme cases. It would seem that this fact is of great importance and should be properly recognized so that engineers may not be misled by the suggested use of the formula $\sqrt{(A^2 + B^2)}$, and may not use the sine meter without fully appreciating the limitations of its usefulness.

**Mr. H. D. Wilkinson** (*communicated*): The paper contains a comprehensive survey of power-factor-correcting machines and appliances, and gives a useful review and criticism of existing tariff rates. But perhaps the best part is in the investigation into the most economic plant which should be used for power factor improvement, in other words, as to what expenditure in corrective devices is justified on a self-contained power plant so that the total capital cost is a minimum. The author shows that the power factor at which it is financially economical to operate the system is a function of the ratio of cost per kVA and per kW of the correcting and generating plants respectively, by the formula $\cos\phi = \sqrt{(1 - a^2)}$. This puts into mathematical form the truism that the more costly the corrective device the less the power factor of the system can be economically improved. In other words, the greater the amount paid for power factor improvement per kVA injected, the less the power factor can be improved with a maximum saving in total cost. This shows, therefore, what an important part would be played in the raising of power factors on distribution systems by the cheapening of corrective devices, and how much more could be done economically with low-priced phase advancers. On the question of tariff it is undoubtedly correct, as pointed out in the paper, to give a financial inducement to the consumer to maintain a high power factor, but I am not convinced that the power factor on the consumer's peak load should alone be considered in the framing of tariffs. If his peak load coincides with the peak load on the supply undertaking's generators and transmission lines, that is no doubt the period most difficult to cope with, but it is almost certain that the consumer's power factor is higher during the peak-load period than at other working hours, and it would appear to be more equitable to the consumer and more advantageous to the supply undertaking to base the tariff on the average power factor. This could easily be observed by taking the percentage ratio of the readings of two single-phase cosine meters connected in two phases, while the arithmetical sum of the pair gives the total units consumed. The author has done well to point out the economically unsound tariff of price per unit based solely on power factor. In conclusion, I should be glad if Prof. Miles Walker in his reply would give us a little further information on the low-frequency a.c. excitation of synchronous induction motors, which he gave the impression of being so much more efficient than d.c. excitation.

[Prof. Miles Walker's reply to the discussion will be found on page 134.]

## North-Eastern Centre, at Newcastle, 13 November, 1922.

**Mr. J. M. Heslop**: It is almost a platitude to say that the power factor problem has become of supreme importance to the electricity supply industry, for it is a characteristic of alternating-current distribution, whose field of influence is already wide and its significance rapidly increasing. The transformer and the induction motor—two appliances whose invention has facilitated the expansion of electricity supply and distribution to an extent which can probably scarcely be over-estimated—each possesses a characteristic, i.e. the need of magnetizing current, which in its present-day dimensions is becoming a source of embarrassment. The problem of supplying this magnetizing current has become of such importance that in a multiple-station undertaking it is sometimes worth while to relieve all but one of the stations from wattless power and transfer the whole of it to the remaining station. One American undertaking, for example, generates the whole of the wattless power of the system (30 000 kVA) by steam during the summer, in order that a distant hydro-electric station may operate at unity power factor and utilize to the full the ample flow of water then available. While certain portions of the transmission and distribution system contribute their quota to the total magnetizing current required, I think it may safely be considered that the widespread use of the induction motor is the principal source of the trouble. The author rightly lays emphasis on the view that the consumer cannot be absolved from complicity in the trouble, and on this point I would reiterate my remarks in the discussion on Mr. Carr's paper, namely, that the man who takes excessive wattless current to suit his own convenience should pay for the privilege of so doing. This paper contains an excellent summary of the possible methods of making him do this. The magnitude of the problem can be visualized when one considers that under present conditions of working in this country there is annually incurred, at a very modest estimate, an excess expenditure on coal alone of well over £500 000 beyond that which is necessary, and in addition to this there must be an unproductive capital expenditure of not less than 20 million pounds—expenditure which could have been applied to new connections or in other revenue-producing directions had it not been for the power factor bogey. The author says on page 92: " It is, therefore, to the supply company's interest that the consumer should have a good power factor not only at peak load, but also at lower loads." I should prefer to re-write this statement somewhat as follows: " It is the duty of the consumer to have a good power factor not only at peak load, but also at lower loads, for in the absence of a power factor clause in the tariff the man with a good power factor on his installation is bearing part of the standing charges which ought to be met by his neighbour." The remedy for the evil of bad power factor is two-fold; the first stage is preventive and consists of missionary work amongst consumers; the second stage is punitive and involves the imposition of stiff penalties for bad power factor, with a corresponding bonus for improvement. The corrective methods which may be employed are numerous, as can be seen from the paper, and it is not feasible to say dogmatically that any one is the best. Each has its proper sphere, but of the importance of the problem and the value of the paper there is no room for two opinions. The subject of power factor correction is receiving a great deal of attention at present, but not more than it ought to have nor more than it will have as time goes on, for it is one of the foremost problems facing electricity supply undertakings to-day. Power factor is, in fact, becoming for the electricity supply industry somewhat of a Frankenstein, and it has occurred to me that the whole power factor question is really a wonderful advertisement for the high-tension d.c. system.

**Mr. T. Carter :** The practical development of our art and of our industry has been bound up to an extraordinary extent with the work of Dr. Kapp. In 1885 and again in 1886 he read papers on dynamo design that threw a flood of light on much that was then dark, and now he has left behind him one that will certainly be of enormous assistance to us all in the consideration of a very tangled and difficult problem. It is, I think, particularly useful in the section on synchronous induction motors, because of the details of designs collected there, and because of the clear way in which it shows that this type of machine to have a respectable overload capacity must work at a leading power factor, or, if that is undesirable, an abnormally large machine, correspondingly expensive, must be chosen. Written by an independent expert, the paper is free from bias ; all manufacturers and suppliers are apt to have their own fancies about what is best, but here we have a general impartial survey of the whole problem. Although a simple rule is given for the amount by which it is useful to improve power factor in a new and straightforward case, it is carefully pointed out that these simple cases seldom occur, and the most diverse considerations have to be taken into account in settling the best course to pursue. The counsel given is to apply power factor improvement with discretion and not to imagine that the more the power factor can be increased the better. The limits of the several possible devices are clearly shown. When correction has to be applied to an existing installation, no nice balancing of relative costs is usually possible, and only a rough approximation can be made to the most economical amount of improvement. The injected kVA are represented by $(\tan \phi_0 - \tan \phi)$, and the improvement in power factor is represented by $(\cos \phi - \cos \phi_0)$, and since $d \tan \phi / d \cos \phi$ is a minimum when $\cos \phi$ is $\sqrt{\frac{2}{3}}$ or 0·8165, correction is most cheaply obtained at that value. But the curve of relative rates of change of $\tan \phi$ and $\cos \phi$ is approximately horizontal between $\cos \phi = 0 \cdot 60$ and $\cos \phi = 0 \cdot 95$, both lagging, and practically exactly so between $\cos \phi = 0 \cdot 70$ and $\cos \phi = 0 \cdot 90$, and the correction required for a given amount of improvement is reasonably constant within this range of values. Outside this range, including, therefore, a change from lagging to leading power factor, the kVA required for a given correction become excessive. It is so difficult to get exact data that usually neither consumers and their advisers on the one hand, nor manufacturers and suppliers on the other, are in a position to furnish information to serve as the basis of a just bargain. All purely commercial bargaining is bad both when it is based on guesswork and when it is not ; suppliers throughout the whole country should make up their minds to a principle, and adhere to it. One supplier comes to a consumer and says that the power factor of his motors must not be less than 0·90. When he is asked whether he means at full-rated load, or at full ordinary duty, or under any conditions of load whatever, he begins to feel doubtful. Another says that new apparatus should work at unity power factor, and that it would be even better if a slight leading power factor were used. That is true, but better for whom ? And how is the ordinary consumer, even the large and well-advised consumer, to know when the terms offered are fair both to him and to the supplier ? I know of cases where important consumers have complained that the price adjustment for variations in the price of coal is unjust to them, and they have supported their plea by quoting figures. They may be quite wrong, but an independent investigation of the effect of all sorts of varying factors on the cost of production would restore confidence, and would react to the benefit of the suppliers. There is an infinite variety of applications of electrical driving. Some of them require a large number of small motors, while others can use a few large motors, and there is much to be said for the principle that a consumer should not be penalized because he is a small-motor man, whose installation will tend to work at a lower power factor than that of the large-motor man. The vital question is whether each is doing his electrical driving in the best possible way. If any consumer so arranges his drives that his power factor is needlessly low for his type of installation, he ought certainly to pay for that bad design ; but so long as he does the best possible for his own job, the suppliers ought to be satisfied without requiring him to pay more per unit because of things over which he has no control. After all, power factor difficulties arise because suppliers use alternating current for their own convenience, and not for their consumers'. The paper suggests that it is detrimental both to the supplier and to the consumer if the power factor is low : I suggest rather that the bulk of the burden is on the supplier, but it is not of his own choosing, and he ought not to grumble at the characteristics of consuming apparatus that must be used merely because he offers an alternating-current and not a direct-current supply. I think that suppliers should not expect to be recompensed by each consumer in exact proportion to the badness of his power factor for their greater expenditure on plant ; they have a monopoly of the right to supply, and they are, therefore, public servants, bound to consider each consumer from his point of view as well as from their own. By being essentially fair to each member of the community they will be fair to the whole. That is one reason why the maximum-demand system of charging is, as the author points out, so much better than the others ; and even that system should be carefully applied when the fixed payment is not purely on a kWh basis, but on a kVA-hour basis or on one intermediate between the two. I should be inclined to fix, as the ideal, not unity power factor in every case, but some figure suitable to the type of installation, perhaps as high as 0·95 in the best cases and as low as 0·75 in the very worst, depending on the average size of motor that ought to be employed for the work and its usual best commercial power factor. I would then determine the maximum demand figure from the maximum kW demand by multiplying it not by 1/(energy factor) but by (ideal power factor)/(energy factor), so that if a consumer using small motors were enterprising enough to put in a type with unity power factor he would benefit comparatively more, as he justly should, than the customer who has larger motors, since their power factor is already nearer to unity. For example, taking the symbols at the end of the paper, assume two consumers, A and B, each with a maximum kW demand of 1 000, but let A have an ideal power factor of 0·90, while B's figure is only 0·80. Then $P_0 = 1\ 000$; and let $m = £5$ per annum, $U = 2\ 000\ 000$, and $d = 0\cdot48$d. Suppose each consumer's average power factor is only 80 per cent of his ideal power factor, namely, 0·72 and 0·64, respectively, then A will pay £11 000 per annum and B £11 800, a difference of about 7 per cent, under the ordinary maximum-demand system; whereas if each of them improved his power factor to unity he would pay £9 000, although it is much more difficult for B than for A to reach unity power factor. But if the ideal power factor were used for the purpose of discrimination, and both consumers were still to work at 80 per cent of the ideal figure, each would pay the same amount, namely, £10 250 on the basis of the assumed rates, and if each of them then improved his power factor to unity, A would pay £8 500, while B would pay only £8 000, which would recompense B for his greater enterprise. It should be understood that the figures used are merely assumed, and probably the rates under the discriminative system would need to be higher than under the present maximum-demand system so as to maintain the requisite total revenue; but the comparison between A and B at each stage is correct in kind, and I suggest that some such scheme as I have proposed would permit the conclusion of agreements between suppliers and consumers on a correct, logical, and mutually equitable basis. The essential problem is: A certain total sum must be received from the whole body of consumers in order that the supplier may have an adequate revenue: how is the demand for that total sum to be apportioned amongst the consumers so that each may pay his fair share? It is this question of the determination of the just incidence of the charge on individuals that I think might be solved by the adoption of what I have called a discriminative system, which is a simple modification of the ordinary maximum-demand system. The author uses the term "energy factor" in a particular sense, and I think that the latter part of the paper would be more clearly followed if special attention were drawn to it where it is first used in the paper, perhaps by a footnote defining it more specifically. It would, in fact, be an advantage if it could have a special symbol instead of the common cos $\phi$. One of the few slight weaknesses in the paper is in its symbols: $P$ is used with different meanings in different places, and so is $\phi_0$. The terms "cosine meter" and "sine meter" are also used in a particular sense in the paper, and without definition their meaning may not at first be obvious; here again I should like to suggest that Professor Miles Walker might, with advantage, add some explanation.

**Mr. A. B. MacLean**: The author states on page 93 that "we may consider the installation of rotary condensers by consumers to be financially unsound." I am inclined to think that this statement requires some modification, as it appears to me that with the tariffs now offered by some supply companies, in which the power factor of the consumer's installation is taken into account, the installation of a rotary condenser should effect a considerable reduction in the total charges for current. If we take the example worked out by the author, apply one of the tariffs mentioned by him as a pre-war tariff, and alter this to present-day conditions, I think it can be shown that the installation of the 600-kVA condenser will show a good profit. In the example the maximum demand has been taken as 1 000 kW at a power factor of 0·75. The total kVA demand is, therefore, 1 333. After the condenser is installed the peak load would be 1 036 kW and the total kVA 1 075. The power factor of the installation is, therefore, raised from 0·75 to 0·965. If we take the tariff given on page 106, viz. £1 per quarter per kVA of maximum demand plus 0·25d. per unit, and bring this up to what would probably be a corresponding present-day tariff, we should have to allow an increase in the demand charge to cover extensions to the company's system at prices much greater than pre-war figures, and the unit charge of 0·25d., which is largely governed by the cost of coal, would probably have to be increased by more than 100 per cent. I suggest that the corresponding present-day tariff would be approximately 25s. per quarter per kVA of maximum demand plus a flat rate of 0·55d. per unit. Taking the author's figures of consumption, the cost of current to the consumer before and after the rotary condenser is installed would be as follows:—

| | |
|---|---|
| *Before installation of condenser.* | |
| 1 333 kVA, at £5 | £6 665 |
| 2 300 000 units at 0·55d. | 5 270 |
| | £11 935 |
| *After installation of condenser.* | |
| 1 075 kVA, at £5 | £5 375 |
| 2 383 000 units at 0·55d. | 5 460 |
| | £10 835 |

We therefore conclude that the consumer by installing the rotary condenser reduces his total bill for current by £1 100. This is a reduction of 9·2 per cent in the total cost of current. The author takes a figure of £3 per kVA as the cost of the rotary condenser, but I believe that at present-day prices this should be considerably less, and that the cost of the 600-kVA condenser should not be more than £1 200. A machine of this kind should need very little attention, and the average consumer installing it would probably not require to employ any aditional labour, but could make arrangements to have the machine looked after by the existing staff. The cost of attendance on this machine would probably not exceed 10s. per week. The total costs involved in the use of the rotary condenser would therefore be covered by the following :—

| | |
|---|---|
| Labour at 10s. per week .. .. | £26 |
| Interest, depreciation and maintenance at 15 per cent.. .. | £180 |
| | £206 |

If we subtract this figure from the total saving in the cost of current, we arrive at a net profit to the consumer of £894. Referring to the different types of synchronous induction motors described, I presume that the rotor of the machine indicated in Fig. 4*d* has a two-phase winding, that the two phases are exactly similar, and that each covers one-half of the pole-pitch. If this assumption is correct, then each phase carries the same current, and the distribution of magnetic flux produced by the rotor current alone would have a wave-shape with a sharp peak. If the voltage of supply to the motor varies approximately as a simple sine function, an additional flux of third-harmonic frequency would have to be produced by a current in the stator, i.e. the motor draws a magnetizing current from the line of third-harmonic frequency. This, of course, may be of very small magnitude, but I should be pleased to have Professor Miles Walker's comments regarding the possibility of such a current being produced by this machine.

[Prof. Miles Walker's reply to the discussion will be found on page 134.]

## NORTH MIDLAND CENTRE, AT LEEDS, 21 NOVEMBER, 1922.

**Mr. H. E. Yerbury :** The technical and mathematical part of the paper admirably covers the field, and I shall, therefore, confine my remarks to the commercial aspect. As supply engineers, we know that a low power factor is a condition which confronts us—and not a theory. I submit that it is unreasonable to suggest that any consumer should take steps to improve his power factor unless a substantial rebate is given by the supplier. Every individual installation should be studied before a decision is made as to whether it is desirable and economical to install a device which alters the characteristics of the motors, or to deal with the problem of low power factor with static condensers on the cables supplying such motors. If the characteristics of the motor are altered, then the total costs involved must be taken into consideration. For instance, in many works no d.c. supply is available, hence the cost of a d.c. generator and the d.c. energy should be added to the cost of the phase advancer. This is not an expensive matter but apparently it is not taken into account in the paper. It is quite obvious that the improvement of power factor is tied up with the question of tariffs. A two-part tariff is, I think, the fairest all-round system of charging. In Sheffield we charge large power consumers £4 per kVA of maximum demand plus 0·25d. per unit, plus a sliding scale based on coal at 10s. a ton. Incidentally, a coal clause disregarding calorific value can be deemed neither scientific nor equitable. I think we can pass over the Arno system of charging, as it is hardly applicable to British practice. I think that the system adopted by the Clyde Valley Electric Power Company is the best submitted, although to my mind it is a debatable point as to whether a consumer of 250 kW should be charged a 20 per cent higher maximum-demand rate than a consumer of 1 000 kW. It is conceivable that the smaller installation could be running at a very high load factor compared with the larger installation, in which case the former may be of greater benefit to a supply department. A very great service has been done to the industry by the Electricity Commissioners in the 1922 Act. Under the Electric Lighting Act 1899 a consumer could elect to be charged on either a kVA or kW basis. Happily, that clause is now repealed and a supply authority can decide to charge any consumer either on a kW or on a kVA basis. For the sake of economy and efficiency I think that steps should be taken to enforce the system of charging on a kVA basis as soon as possible, ever remembering the word "expediency" and all that that implies, and that a satisfied consumer is the best advertisement for electricity. At the present time I find that it pays a consumer with a load factor of less than 30 per cent to be charged on a kWh basis, and only where his load factor exceeds about $33\frac{1}{3}$ per cent does it pay him to be charged on a kVA basis. Personally, I think that the best system for the supplier is to declare the minimum average power factor, say 0·8. Then the price per kVA of maximum or average demand above or below that declared power factor should be varied, and in addition a flat rate per kWh should be charged. To give a consumer the advantage of night-time phase-advancing might be advantageous to a power company with long transmission lines and only power loads, but that practice on a town's general supply cannot, I think, be generally recommended. It appears that three instruments are essential to ascertain a consumer's maximum or average demand, and also his kVA and kW consumption. There has been much discussion as to whether one should charge on a maximum demand or average demand over a predetermined period. I think that the average is fairer, and in most cases the average is taken over a period of approximately 20 minutes with a thermal instrument.

**Dr. T. F. Wall :** I have recently been engaged in studying a new device for the phase-advancing of induction motors, in which the electrical energy is stored during one part of the cycle in the form of chemical energy and during the remainder of the cycle is released in the form of electrical energy. The principle is thus the same as that of a secondary battery, such a battery being, in effect, an electrical condenser of very large capacity. Suppose two lead grids, say A and B, are pasted with red lead ($Pb_3O_4$), immersed in dilute sulphuric acid, and connected in circuit with an alternating-current supply. Then during one half-cycle the paste of one grid, say A, becomes oxidized to the higher oxide and the paste on the other grid becomes reduced to the lower oxide. In other words, the arrangement corresponds to an accumulator on charge, the grid A being the positive plate. During the next half-cycle the action is reversed, and the cell becomes discharged and re-charged in the opposite direction. It is found that the action is greatly assisted and improved if the cell works at a relatively high temperature, say about 80° C. When the temperature is so increased the gassing becomes negligibly small and the inherent power factor becomes very low, that is to say, the losses are low and the phase advance of the current on the potential difference is large. In Fig. B this effect is clearly shown. The readings were taken by connecting a cell to a low-frequency supply and immersing the cell in a bath the temperature of which could be regulated. It is clear that a very considerable improvement of the action of the cell takes place up to about 70° C. and subsequently the improvement is less marked with increase of temperature. In Fig. C the corresponding values of reactance voltage are plotted as a function of the temperature. The effect of increasing the temperature appears to be two-fold, viz. (i) The specific resistance of the electrolyte is reduced ; and (ii) the chemical activity of the components of the cell is stimulated. With regard to the second effect, it is of interest to note that the action of a certain type of lightning arrester is based on the fact that the chemical stability of lead oxides is very easily upset by relatively small temperature-rises. Dry lead peroxide ($PbO_2$) has a specific resistance of about 1 ohm per inch cube, the resistance varying with the pressure with which the powder is compressed. At a temperature of about 150° C. lead peroxide is reduced to red lead ($Pb_3O_4$), which has a specific resistance of about $24 \times 10^6$ ohms per inch cube. At slightly higher temperatures red lead is reduced to litharge (PbO), which is practically an insulator.* In Fig. D the results of some tests on a 4 b.h.p. induction motor are given. These tests were made by two post-graduate students, Messrs. G. Allsop, M.Eng., and C. E. Robinson, M.Eng. The data were obtained with one cell in series per rotor phase, and clearly show the beneficial effects to be obtained by this type of phase advancer. The tests also showed (see Fig. E) that the efficiency of the motor was greater when the phase advancer was in circuit than when the machine was running under the normal conditions of short-circuited rotor.

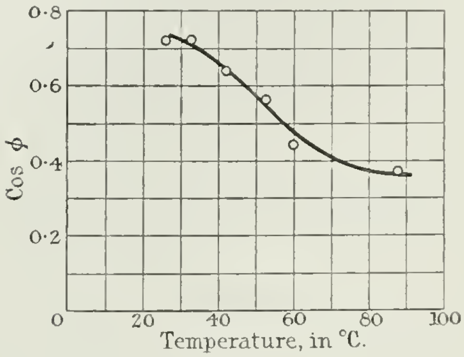


Fig. B.

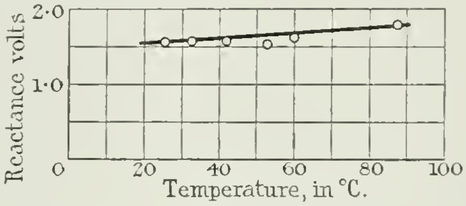


Fig. C.

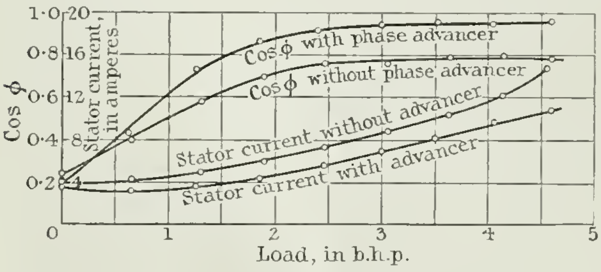


Fig. D.

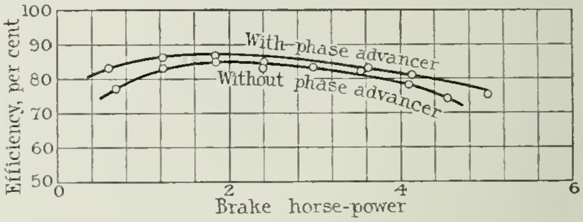


Fig. E.

**Mr. J. W. J. Townley**: The paper is very interesting to all engineers concerned in the generation or distribution of alternating current, but what impresses one on reading it is the fact that so much has been done in the design and development of phase advancers and that so little use has been made of them in practice. The whole trend of the paper has been in the direction of encouraging the consumer to improve his power factor, but I think the improvement of the power factor of the system should be kept in the hands of the supply authority, who can put down phase-advancing plant in those areas where the mains are fully loaded, and when mains extensions are carried out can transfer the phase-advancing plant to another part of the system. It is usually the case that more copper has to be laid down than is required for the needs of the moment, owing to the heavy cost of reinstatement, and this copper might just as well be loaded by consumers who pay a standing charge based on their kVA demand. One has only to compare the tariffs of different supply authorities to note the very great difference between basing the standing charge upon kW and upon kVA, one undertaking quoting, say, £4 per kVA, and another £8 per kW. If the consumer who is paying £4 per kVA has a power factor of 0·7 he is actually paying £5 14s. per kW. That difference represents a very substantial increase in the revenue of the supply undertaking, and this will be lost under present methods of charging, without much compensating advantage if the power factor improvement is left entirely in the hands of the consumer. I have had some experience with the Kapp oscillating phase advancers on two induction motor-generator sets, each of 1 500 kW capacity, ordered in 1914 and installed in 1916. These machines have operated in a perfectly satisfactory manner, and my experience has been such that I would always recommend the installation of induction motor-generators with phase advancers rather than synchronous machines, as the former give all the advantages of a synchronous set but with the great additional merit of simplicity of starting.

---

* *General Electric Review*, 1918, vol. 21, p. 597.

**Mr. W. E. Burnand :** The question is essentially divisible into two parts, one applying to the supply authority and the other to the user. So far as the supply undertaking is concerned it is a matter of simple arithmetic and a little judgment to correct the power factor when it is necessary and advantageous. As regards the consumer, the reason that this power factor question has become of importance is unsuitable tariffs. I should like to point out that the current taken by motors and inductive apparatus is quite easily divided into two parts, one at unity and the other at zero power factor, and it is easy to get meters to register these readily. The ordinary induction meter indicates the power units, and it is quite easy to get a meter that will show the consumption at 90° from those, i.e. the wattless kVA. Trouble results from this lagging current, which, while it may be wattless, is not, however, useless. The magnetizing current acts as a fulcrum for the power current to work upon. The wattless current costs something like $\frac{1}{4}$d. per kVA-hour delivered to the consumer. Why not install a meter and sell three units for 1d. and make a profit on it ? I think the consumer would understand that. If these magnetizing units can be sold to him at a profit, I think it will be more satisfactory than having to make complicated calculations and using power-factor terms which would not convince the consumer that he was being charged on a fair basis. The paper describes really a very comprehensive collection of devices for improving the power factor, but they are all of them expensive, and I think most people would call them complicated. The number of parts is often more than in the original motor the power factor of which it is intended to correct. They also lower, as a rule, the efficiency of the plant. It is necessary to offer a strong inducement to a consumer before he will use such an arrangement. Excepting static condensers, these are chiefly adapted for large motors, which need not, however, have a low power factor, if run from $\frac{1}{4}$ load upwards, so that it ought to be exceptional to find a low power factor on a large motor. The paper gives me the impression that the power factor is very materially lower with these special machines with the exciter not working than in a standard machine. That is due to the larger air-gap and the higher density of the magnetic flux in the teeth of the special machine. It is impossible to make a small motor which will have as high a power factor as a large one, but it would appear possible to improve this without great expense or complication. It means making the auto-transformer part of the starter about four times normal size, and running the motor when on light loads on a lower-voltage notch on the starter. The cost would be small and, so far from introducing a complication, strengthens a weak spot. Even with the existing tariffs this will generally be profitable. The reason is that the auto-transformer if it is properly designed is a more efficient transformer than the motor itself. Therefore, with the motor at $\frac{1}{4}$ load the power factor will be over 0·7 and the efficiency will be practically equal to that with the motor running on full load. Losses in the motor are saved that will seldom pay less than 20 or 30 per cent on the original extra cost. Under present conditions people will not lay out more money than necessary, and these are not in such great demand as they used to be, but if there were a proper tariff, and if consumers had to pay for the magnetizing current, the power factor would be raised and the sales would increase.

**Mr. W. A. A. Burgess :** As a large user I should like to refer to a method of power factor improvement which has not been touched upon, i.e. the improvement of power factor by what is called in America "electrical service," that is, advice to the consumer as to the proper use of his electrical equipment. I had occasion to take over a works containing a large number of motors and found that the total power factor was 0·41. There was obviously something wrong and I found a number of motors running much hotter than their loads warranted. On some it was found to be a question of excessive air-gap. As there may be many users who do not know what air-gap means to them, and do not care, they should be kept informed by the power supply authority in whose interests it is to secure a good power factor. To give an instance of this, I found in the works in question that it had been the practice when a rotor fouled a stator to take out the rotor and take a cut off it in the lathe, to the detriment of the power factor and the insulation of the rotor laminations, whereas what really required attention was, in nearly every case, the motor bearings. The improvement of air-gap is often erroneously thought to be impossible, but I found it profitable to buy a new rotor in many cases where the motor was otherwise in good condition, while in other cases the only alternative was to replace the entire motor. If service advice had been given, neither contingency would have arisen and the supply authority would have had a better power factor. After improving the air-gap the various motors must be arranged to carry something like their normal load either by changing over or getting additional loads transferred to them. By a combination of these methods and a rigid specification for new machines the power factor of the works in question was raised to 0·7, no small achievement where 90 per cent of the load consists of induction motors. In connection with the general question of power factor I should like to ask Prof. Miles Walker if he can tell us the exact relation of the power factor to the starting torque as far as the economic design of a commercial motor is concerned. It has been found on occasion that certain motors of the squirrel-cage type with a remarkably good power factor at half and full loads are apt to fail to start up against full load and in some cases less than full load. Is this a case of locking owing to a too small air-gap, or merely an accidental coincidence of low rotor resistance? I fail to see why there should be such a extreme difference between the costs of the various apparatus for correcting power factor. The figures, given by the author, of 10s. to £5 or £6 are surely a standing reproach against certain manufacturing sections of the industry. For less than 10s. per kW on a reasonably sized motor, say one of 500 h.p., one can get a Kapp vibrator complete with switchgear and the provision for excitation. I recently purchased one which is of the horizontal type with ball bearings. It was installed, connected and put into operation and has up to the present required no attention beyond general running maintenance. It improves the power factor most satisfactorily within the limits of the capacity of the motor to which it is connected, and has given no trouble whatever. It seems to me, however, that power factor improvers of the Scherbius and the Kapp vibrator type are only more or less able to supply power factor correction equivalent to the load on the motor, while a synchronous motor has its full capacity available for power factor correction at light loads as well as when doing useful work. One speaker raised the question of the cost of excitation. In the case in question the excitation was by a belt-driven 0·4 kW generator from the main shaft, and no trouble whatever was experienced. The cost of static condensers, which are a useful form of apparatus for the improvement of power factor, is alarming. That one should have to pay 3, 4 or 5 times as much for a static condenser as for a static transformer indicates to my mind a complete failure on the part of the manufacturers to cater for the industry at a reasonable price. It is a distinct advantage to be able to apply power factor correction to small motors, which probably form the bulk of a power-supply load and the aggregate power factor of which should be kept as high as possible. I think there will be very few power-supply authorities who do not desire all motors connected to their mains to have a power factor as near unity as possible. The question of improving power factor by static condensers has given me considerable food for thought, and as an alternative to a power-factor-improving device on the supply mains it has occurred to me that one might be able to use some form of condenser starter. The old water-resistance starter had an appreciable capacity, and if it were possible to go beyond that and use a variable-condenser device for starting instead of the customary auto-transformer starter, and then leave the condensers on the line while the motor is running and switch them off only when the motor is stopped, I think we should get something cheap, efficient and acceptable to supply authorities and consumers alike. I am quite aware that there are difficulties in the way, but I think they need not be insurmountable in these days. In regard to tariff, as a consumer and also as a supplier of electricity I agree with what has been said in connection with giving the consumer a fair deal. The consumer must be given all the satisfaction possible, and he must be shown that he is getting value for his money in every tariff offered to him, if the business is to grow and be profitable.

**Mr. A. F. Carter:** The manner in which some people—and in particular mechanical engineers—buy motors should receive attention. They have a machine they wish to drive and, as the manufacturers do not know what horse-power is required, they take a guess and add 50 per cent to it, and the result is perhaps a 10 h.p. motor for a 6 h.p. load. This is repeated, with the result that the mains are loaded up with useless kVA, whereas the energy actually used is very small. I think that much could be done by assisting the mechanical engineer in the selection of the powers required for his various loads. I recently had occasion to measure the load on a small motor of 2½ h.p. The watt-hour meter was registering ½ kWh per hour. This ridiculous—though not unusual—state of affairs should be remedied. On page 100, data relating to the Birmingham Corporation Electricity Supply Department are given, and it will be seen there that approximately one-quarter of the load is composed of rotary converters and one or two motor-generators with a corresponding high power factor balancing three-quarters of the load, which consists in the main of small motors at a low power factor, giving an average power factor of 0·79. No doubt if motors were better selected for their work the power factor could be brought up to at least 0·85 in the above case. I feel that one cause of difficulty is the fact that in some cases supply engineers rule that the current taken from the line must not exceed 125 per cent of full-load current. This often results in a larger motor being used than is necessary (particularly with squirrel-cage motors) in order to keep down the percentage overload current at starting. If the 125 per cent rule were suitably altered and more attention given to the selection of appropriate starting switchgear, no difficulty would be found in loading motors up to the 100 per cent mark.

**Mr. A. V. Clayton:** I think that the question of power factor is a burning one, especially, I presume, for supply companies, but I think that they are, to a large extent, to blame for that. Prior to the war I was engaged in designing machines on the Continent, and even small motors were being built with high power factors; for instance, machines of 6, 8 and 10 h.p. at 1 000 r.p.m., and of 10, 15 and 20 h.p. at 750 r.p.m. had power factors of 0·93 to 0·945 at full load, and of about 0·89 at half load. During part of the same period I was engaged in designing machines for some English manufacturers, and as the power factor permissible on the mains of the supply companies here was 0·8 we took advantage of this to design motors for the English market, regardless of power factor, so that they were the cheapest. Thus, whilst I was designing motors with power factors of upwards of 0·9 for use on the Continent, I was also designing machines with power factors of 0·8 and upwards for use in England. As regards the cost of rectifying low power factor by means of phase advancers, some little time prior to the war I built two 20-pole, 250-h.p. machines for use with Kapp vibrators as a trial of cost. They were bad motors to design from the point of view of power factor, because they were comparatively small machines for the number of poles. As the number of poles in a machine increases, so the difficulties in obtaining good power factor increase, because the power factor depends to a large extent on the magnetizing current, and hence as the number of poles in a given size of motor is increased, the required magnetizing effect, and, therefore, the magnetizing current, is also increased. The two particular machines referred to were designed by me at Dr. Kapp's request to give the cheapest possible machine regardless of power factor, but with due attention to temperature-rise. Fulfilling these conditions the calculated natural power factor was 0·835 and on test 0·84. The cost of the Kapp vibrators was approximately 33 per cent of the cost of the motors, and even at that figure there was no profit to the makers on the manufacture of the vibrators. Had I utilized a little more material in designing the motors I could have improved their power factor to 0·92 at full load and to 0·87 or 0·88 at half load. The increase in cost of manufacture of the motors would then not exceed 12 per cent of their former cost, because the mechanical parts of the motors would remain the same, the labour would be practically the same and it would only be a question of using a little more active electrical material to obtain the higher power factor. The question of the length of air-gap, which of course has a very large bearing on the power factor of motors, is entirely a mechanical one and should receive due consideration with regard to the diameter and axial length of the rotating part and the rigidity of the mechanical parts of the motor. One speaker rather gave me the impression that the air-gap could be adjusted after the motor is built; this, however, is not possible except by building a new rotor, rather a costly proceeding. I was surprised to notice in the paper a statement that private enterprises had no interest in increasing the power factor of their load, and that the author had no personal experience where such cases occurred. I have known many cases of private generating stations desiring to obtain better power factors, and I can mention two cases in this country where I think it will be admitted that the improvement in the power factor of their own load was a distinct advantage. One was the case of a large cotton mill where a 1 000 kW generator was installed. This generator was an old type, low-speed machine and had a rather small magnetizing effect so that in time, as the load increased, it would not hold its voltage and the steam engine could not be utilized to anything approaching its full load. There were a large number of small motors, loom motors, etc., having bad power factors, and eventually a stage was reached where either further generating plant would have to be installed or else the bad power factor of the load would require rectification. This was done by installing a synchronous phase advancer at only a fraction of the cost of new generating plant. The cost of this synchronous phase advancer, or "rotary condenser" as it is sometimes called, was not nearly the cost (£3 per kVA) mentioned by the author. The cost was, in fact, considerably less than half this and at the time it was installed in 1917 was less than £1 per kVA injected, including the cost of exciter, etc. I think that the author also states that the cost of a synchronous phase advancer is the same as that of a generator of like capacity in kVA. This is scarcely the case, because in the phase advancer the mechanical parts are negligible and we only have to deal with the electrical energy; moreover, the speed can be chosen to suit the most economical design, whereas in a generator the speed is determined by that of the prime mover. (In this connection the fact must not be lost sight of that the highest-speed machine is not necessarily the cheapest.) Having regard to the electrical and mechanical conditions, each size of generator, or its analogy the synchronous phase advancer, has a definite speed for a given kVA output at which it can be designed most economically, and this speed nearly always differs widely from the natural speed of a prime mover of similar capacity. Many speakers have mentioned the number of small motors used on a supply company's network and it would be very interesting to know the average size of motor connected, because on that depends whether phase advancers could be used extensively to obtain a commercial advantage. In this connection I might mention that during my last year abroad the turnover of our works was a little over 110 000 h.p. of electrical machinery, and although machines of 500, 700 and 1 000 to 2 000 h.p. were frequent and nothing smaller than 3 h.p. was made, it surprised me to find that the average size of machine produced there was only about 32 to 35 h.p. Phase advancers of the Kapp vibrator type can only be used at a reasonably commercial cost in the case of fairly large motors, and it must be remembered that, apart from the vibrator itself, machinery to generate a supply of direct current must be provided with them (for excitation purposes) unless such supply already exists. Moreover, apart from the cost there is the question of a fairly complicated system involving at least three commutators per motor to be attended to, as against the simplicity of the straightforward induction motor which has done so much to popularize the use of electric power. My experience is that the Kapp vibrator cannot be used to increase the power factor beyond 0·96 to 0·98 (lagging) without disastrous consequences to the commutators, involving much wear and tear and very considerable attention. Rotary converters, also, work much better with a slightly lagging power factor, and attempts to over-excite them usually result in bad "hunting" effects. Kapp vibrators can be used to only a very limited extent, and for the production of an equal effect are probably the most costly piece of apparatus used for phase-advancing. Even on moderately large motors, where their use would improve the power factor from 0·92 or 0·94 up to 0·96 or 0·98, the extra complications involved outweigh the little advantage gained. It must be admitted that the Kapp vibrator gives constant power factor to the motor from about one-third full load up to full load, but large motors are usually fairly well loaded and a power factor of 0·88 or 0·89 could reasonably be expected, even at half load, without the vibrator. I believe that if statistics were made of the various supply companies' networks it would be found that even in all the isolated cases where Kapp vibrators, rotary converters or other phase-advancing apparatus could be employed, the actual improvement at the power station would be trivial, and not nearly so much as could be obtained by the improvement of the power factor of small motors. My conclusion is, therefore, that power factor improvement should be sought primarily by removing the source of the trouble, viz. the bad power factor of the small motors.

**Lieut.-Col. H. W. Watts** (*communicated*): One speaker mentioned that engineers were sometimes responsible for installing a.c. motors which were unsuitable for their work, and thus obtaining a poor power factor. After the war I was acting as consulting electrical engineer for some factories in India and had occasion to superintend the erection of a large number of a.c. motors, the lay-out of which was designed by someone in this country. When they were set to work I found that the power factor of the installation was something under 0·4. The motors varied in size from 1 h.p. to 50 h.p. and the majority were of 25 h.p. I found that the reason of the low power factor was, in nearly every case, due to the motors running on a load far less than that at which they were designed to work. The makers guaranteed these motors to have a power factor of over 0·9 on full load and about 0·8 on half load. By rearranging the motors to run on their proper loads, the power factor was improved and brought up nearer to the requirements of the supply authority, which was laid down as 0·85. I think it an excellent idea for a supply authority to have a clause in its tariff to power users to give the consumer a bonus should his power factor be better than 0·85. The Calcutta Electric Supply Corporation allows such a concession.

[Prof. Miles Walker's reply to the discussion will be found on page 134.]

## LIVERPOOL SUB-CENTRE, AT LIVERPOOL, 27 NOVEMBER, 1922.

**Mr. E. M. Hollingsworth:** The almost universal application of alternating current during the past few years has brought with it the problem of power factor improvement, and to the practice in many cases of installing electric motors of considerably greater power than is necessary, a relic of the direct-current days, is due in no small measure the low power factor with which many supply undertakings are faced. In view of this it is all the more necessary to keep in touch with consumers, and point out the advisability of installing motors suitable for the loads, letting them understand that the alternating-current motor is capable of withstanding considerable overload without any risk of failure. Regarding the various appliances put forward in the paper for compensating for low power factor, it seems to me that in many cases the static condenser has the advantage both as regards capital outlay and operating cost. Of course, in the case of large installations with motors of 100 h.p. and upwards installed, the synchronous induction motor or rotary type of phase advancer should be considered. Some months ago the company with which I am associated installed a static condenser in the small power station of one of their works, and we are very satisfied with the results. Before installing the static condenser the power factor was in the neighbourhood of 0·5, and the question of installing another generator at a cost of £3 500 was under consideration. The static condenser was installed for £700 and has improved the power factor to 0·85, with the result that the two existing generators are capable of dealing with the load. That part of the paper which deals with meters and tariffs is of great interest, and shows how necessary it now is for many supply authorities to adopt a tariff that will encourage power users to maintain the power factor of their load as near unity as possible. With recollections of the difficulty, years ago, of trying to explain to the prospective consumer the intricacies of the maximum-demand system of charge, it is to be hoped that history will not be repeated in this direction and that some suitable tariff will be arrived at which will take into account the power factor, and at the same time be simple enough for the ordinary consumer to understand.

**Mr. L. Breach:** I always feel that this subject is treated from the wrong point of view, and that there should be no necessity to improve the power factor of the system, but rather to improve the design of the apparatus connected to the system. One looks forward to the time when motors and other plant will have embodied in their design the necessary correction gear, and the motor with a high power factor will be started up in the same way as at present; perhaps in the future supply authorities will be able to insist on such plant being installed. Slip-ring voltages of the figure mentioned on open circuit will require special switchgear to protect the operator, and all apparatus must require little attention, because if one tries to persuade a consumer to install correction plant, his argument is that he must not only spend more on his plant, but must also give it more attention when he has got it. "Power factor" is an expression which should be capable of a simpler definition, as many engineers have a very vague notion of what it really means and of the far-reaching consequences in neglecting it. The consumer, of course, knows less; he gets several estimates for a motor, and on looking carefully over the efficiencies and weighing up the question as to whether eventually a more expensive motor with higher efficiency will not benefit him most, finds it will and orders the same. He studies the power factors and dismisses them as not being his business, but the supply undertaking's. In one instance with which we had to deal—a consumer with about 150 kW of proposed load—we installed a 300 kVA transformer in our substation to supply him at 400 volts. An inspector shortly afterwards informed us that the transformers were carrying 277 kVA. On investigation the consumer was found to have an actual load of 132 kW at 0·475 power factor. The matter was taken up with the consumer, who suggested that if our transformers were not big enough that was our concern and not his, as he was quite satisfied with his plant. However, he was finally persuaded to rearrange his motors to get better loading, with the result that he had several surplus motors to help in the equipment of a new factory which he was building. At the present time our system power factor on the peak is 0·95, with a daily minimum of 0·79 and an average of 0·883. This is, of course, exceptionally good and is accounted for by the large number of rotary converters in our converting stations. These converters are run with slightly leading power factor, and on peak load about 22 000 kW of plant of this type is running. There is also about 23 000 kW of 6 000-volt induction motor-generator plant installed in the converting stations, with an average power factor of 0·90 at full load. Perhaps this high power factor was attained by the designers at a sacrifice of safety, as originally we experienced much trouble due to stators elongating and rotors fouling. This was overcome by grinding the rotors, with a corresponding loss in power factor due to the increased air-gap. The d.c. load will not, of course, increase in the future nearly as rapidly as the a.c. load, so that unless some encouragement is given to the consumer or plant greatly improved, we must expect to lose the advantage which we hold at the present time. Up to now we have had no special charges on account of power factor, but the matter is under consideration as we are fully alive to the fact that something must be done. We feel, however, that with the numerous clauses already attached to agreements, the simpler the new arrangement is, the more readily it can be understood. The kVA maximum-demand charge with units charged on the flat rate by a cosine meter (as the author calls it) requires so much less explanation than the "preference and penalty" method, which becomes very complicated. We have considered giving financial assistance to the larger consumers to get them to install phase-advancing plant. In addition, we are constantly trying to persuade smaller consumers not to put in a 20 h.p. motor if a 15 h.p. motor will do the work, and are as constantly met with the reply that they prefer to have something in reserve. Perhaps they are right, but if the designer will produce a good piece of plant with a good power factor we shall agree with them entirely. In the meantime we shall do our best to maintain a high power factor, and we shall look to the motor designer to improve it for us.

**Mr. H. Higham :** The question of power factor improvement is rapidly becoming recognized as one of great importance, and the present paper gives consumers of electrical energy a very useful collection of various kinds of apparatus suitable for the purpose of power factor correction. With regard to the application of the various kinds of apparatus referred to, if a suitable load can be provided for a synchronous motor this method could be applied. If large slip-ring motors are available, phase advancers can be applied if the conditions are favourable. In the case of squirrel-cage motors, static condensers only are applicable. Rotary condensers are sometimes applied to long lines where lagging or leading load is necessary in order to control the voltage and power factor at the end of the lines. In all cases full details of first cost, and particularly of running losses, must be carefully compared before a decision can be made as to which apparatus is most economical. It frequently occurs that the first cost of a static condenser is higher than that of other apparatus put forward for power factor correction, but on comparing the running losses and the amount of attention required, etc., it is found that the static condenser is cheaper in the long run. I have frequently seen cases where a synchronous motor has been put forward for power factor correction, and for doing useful work. In some of these cases the arrangement is not very economical. Take, for example, a system which requires 270 leading kVA to give 90 h.p of useful work. This requires a synchronous motor capable of giving 280 kVA. The losses would amount to 14 kW and at 7 000 hours per annum at 1d. per kWh would cost £410. If, on the other hand, a 90-h.p. motor had been installed to do the useful work, and a 270-kVA static condenser, the losses in the complete equipment would amount to, say, 5 kW, and at 7 000 hours per annum at 1d. per kWh would cost £146, showing a saving of £264 per annum. With regard to the prices mentioned in the paper, viz. 10s. per kVA of correction for a phase advancer when used with a very large induction motor, some figures of the cost when used with motors of, say, 50 or 100 h.p. would be useful, as the greater number of power users are interested in motors of such sizes. I am inclined to think that the cost would then be more in line with that of static condensers. A supply undertaking when determining the charges to be made have to take into consideration the power factor of their system, and if they do not discriminate with regard to the power factor of each consumer it means that consumers with a good power factor have to pay more than they should to make up for those with a bad power factor. Moreover, it is not right that a consumer with a bad power factor should interfere with the voltage of supply, as is the case when working at a low power factor Penalty clauses are nearly always included in agreements but in many cases are not enforced. I believe that if a suitable accurate kVA meter were available, it would be of considerable assistance in helping supply undertakings to arrange their tariffs.

**Mr. F. J. Teago :** I should like to call attention to the footnote on page 90. This can be used to illuminate many of the author's points. Its most important use is that it enables the matter on page 91 to be represented in a graphical form which will appeal to those to whom mathematical equations convey no mental picture of the details involved. Set out the triangle OEI so that the angle $\phi_0$ has a cosine equal to 0·75 (see also the note by Prof. Walker on page 90 and the author's remarks on page 91). Let the length of the vector OE represent the cost of the electrical plant at unity power factor, i.e. £12 000. The length of the vector OI will then represent the cost, £16 000, at a lagging power factor of 0·75, and the length of any other vector between the point O and the line EI will represent the cost at a power factor equal to the cosine of the angle between that vector and the vector OE. Now, to a suitable scale, the length of the vector IE represents the cost of the power-factor-improving plant. If the value of the ratio $c/C = 1 \cdot 0$ then the scale of EI equals the scale of OE. In this particular case $c/C$ equals $0 \cdot 25$, so that the scale of EI is four times that of OE. Mark off from I, along IE, a cost scale as shown in Fig. F and join O to convenient points on this cost scale. Then, on improving the power factor from 0·75 to 0·812, the net saving will be

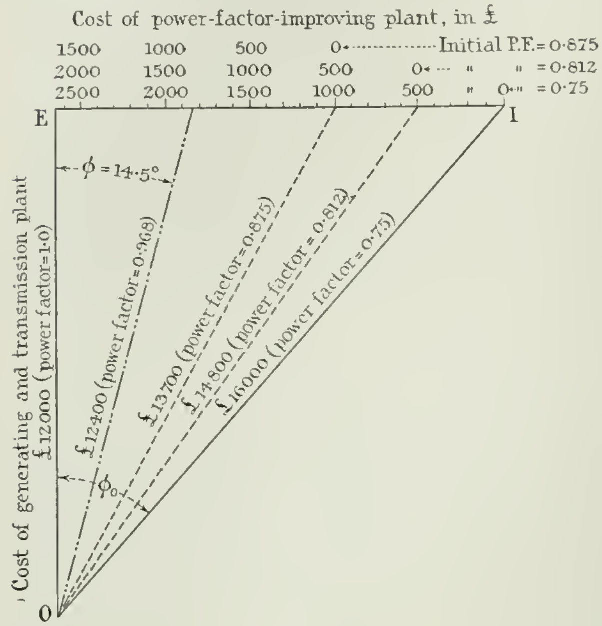

Cost of power-factor-improving plant, in £
1500 1000 500 0 Initial P.F.=0·875
2000 1500 1000 500 0 " " =0·812
2500 2000 1500 1000 500 " 0 " =0·75
E
I
φ=14·5°
£12400 (power factor=0·968)
£13700 (power factor=0·875)
£14800 (power factor=0·812)
£16000 (power factor=0·75)
φ0
Cost of generating and transmission plant £12000 (power factor=1·0)
O

FIG. F.

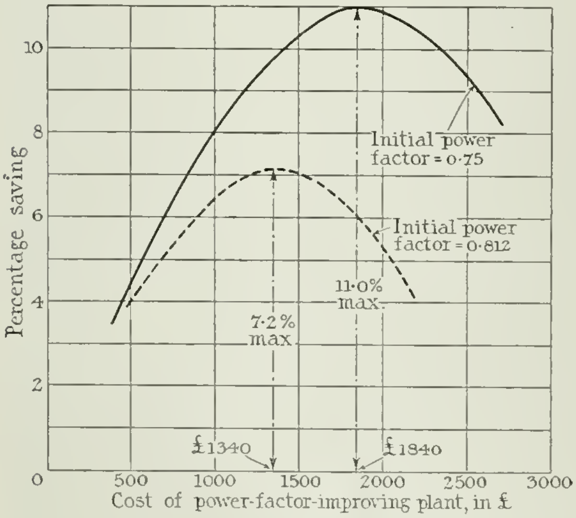


FIG. G.

Original cost of plant — New cost of plant — Cost of power-factor-improving plant

$$\text{or } £16\,000 - £14\,800 - £500 = £700$$

The percentage saving $= 700 \times 100/16\,000 = 4 \cdot 4$ (approximately).

Repeat this for other values of the improved power factor and plot the results as shown by the full-line curve in Fig. G. This curve shows that the maximum percentage saving equals 11·0 and corresponds to an expenditure of £1 840 on the improving plant. From Fig. F it is seen that the angle at which this maximum occurs is $\phi = 14 \cdot 5°$ and that the power factor is 0·968. Now take an angle, to commence with, having a power factor of 0·812. The zero value of the cost of the improving plant under these conditions coincides with the original value, £500. On improving the power factor from 0·812 to 0·875 the net saving will be

$$£14\,800 - £13\,700 - £500 = £600$$

The percentage saving in this case $= 600 \times 100/14\,800 = 4 \cdot 1$ (approximately).

Repeat as before and plot the results as shown by the dotted curve in Fig. G. This shows that the maximum percentage saving is 7·2 and corresponds to an expenditure of £1 340 on improving plant, and it is seen that an expenditure of £1 340 under the new conditions corresponds to exactly the same improved power factor as an expenditure of £1 840 under the old conditions. This constant angle $\phi$ equals 14·5°, the sine of which is 0·25. Thus, as the author points out, $\phi$ depends solely on the value of the ratio $c/C$ and is independent of the original value of the angle $\phi_0$.

**Mr. T. E. Houghton:** I think I am correct in saying that the mathematical determination given in the paper of the most economical value of the power factor to which a system can be brought only applies to a new private installation, and therefore does not hold in the case of a consumer whose present power factor requires improving. Nevertheless it seems to me to be possible to deduce a mathematical relation in this case also. The author at the end of the paper recommends a maximum demand tariff based on kVA. Assuming this to be the case, I find that the economical phase angle for a consumer so charged can be determined from the expression $\sin \phi = Y/X$, where $Y$ = annual charges plus running charges per kVA of phase-advancing plant, and $X$ = charge per kVA per annum of maximum demand. Shorter periods can, of course, be used to suit individual cases. Taking the usual values of $X$ and $Y$, I find that $\cos \phi$ approximates to unity. It is also possible to deduce a formula for the case in which it is desired to reduce the losses in a transmission or distribution system by improvement in the power factor. This is rather more complicated, but I find that the economic phase angle is given by the equation $\tan \phi = (50/K) \times Y/M$, where $K$ = percentage losses at unity power factor, $M$ = actual cost per kW per annum and $Y$ has the meaning given above. In this case also $\cos \phi$ approximates to unity. I think it is significant that the author's expression and those given above all give values of the economic power factor very near to unity, whereas it has been generally accepted that the improvement in power factor should not be carried much beyond 0·9. Turning to methods used for power factor improvement, several speakers have drawn attention to the fact that it is not generally possible to use a synchronous induction motor for this purpose. Taking the case given in the paper of a

1 000-kW installation which required 600 kVA of phase-advancing plant, the most economical power factor at which to operate a synchronous induction motor is 0·707, since the sum of kW and kVA is then a maximum. In the given case, therefore, a machine of 600 kW capacity would have been required, which is, of course, excessive. In a case on which I have been engaged with Mr. Hollingsworth, we had to improve the power factor of a 200 kVA load from 0·5 to 0·9, in order to avoid the purchase of a new generating set. This entailed the injection into the system of 125 leading kVA, and to provide this capacity by means of synchronous motors would have necessitated the installation of a 125 kW motor working at 0·7 power factor, i.e. more than the existing load. In any case, in our business we rarely require a motor of more than 25 h.p., so that power factor improvement by this means is impossible. Vibratory phase advancers were also out of the question, since no d.c. supply was available. The only solution was a static condenser, and this has been most satisfactory. Regarding the question of tariffs, it seems to be generally accepted that the maximum-demand system based on kVA is the most suitable. The metering problem, however, appears to be somewhat complicated. As far as I can see, with the exception of the Aron Meter Company's maximum-current meter, no attempt is made to determine the true maximum kVA, i.e. the maximum kW divided by the average power factor is taken as the maximum kVA. This being so, I should like Prof. Miles Walker to say what is the objection to a polyphase cosine meter, fitted with a Merz maximum kW demand indicator working in conjunction with a single-phase cosine meter connected in the same phase as one of the elements of the polyphase meter. From the readings of the two meters the average power factor can easily be determined, and hence the maximum demand in kVA.

**Dr. E. W. Marchant :** The paper refers to nearly every method of power factor correction, including the use of static condensers. It may be interesting to record the effect of capacity on long, overhead transmission lines. A long, overhead transmission line has very considerable self-induction, but it also has considerable capacity, and in one case that has been calculated of a 200-mile transmission using three overhead conductors each of 0·36 in. diameter, spaced 6 ft. apart, it may be shown that the capacity effect is very considerably in excess of the reactive effect due to self-induction. At 60 periods such a line, if supplying a load of 200 amperes at the receiving end with 60 000 volts between phases at a power factor of 0·9, will require at the sending end a pressure of 70 000 volts, and a current of 175 amperes at a leading power factor of 0·966. This voltage is, of course, low for a 200-mile transmission line, and the constants would have to be varied for a higher pressure. It is well to bear in mind that a phase advancer is specially adaptable to large motors. Some months ago I made an inquiry for one to be used in connection with a 10 h.p. motor, and its cost was very nearly as large as that of the motor. For motors of 100 h.p. or more, no doubt the phase advancer is cheaper as compared with the motor. The rating of the phase advancer for a given amount of leading kVA is only about 5 per cent of the kVA that is to be injected, since the current is injected into the rotor of the motor by the phase advancer at the slip frequency instead of at the line frequency. Consequently, the current required to produce the necessary compensation for the magnetizing current in the stator will have to be supplied at a much lower voltage. If the slip is 5 per cent the voltage injected will be only 5 per cent of that required at the line frequency. For small motors, static condensers are the cheapest method of correcting the power factor. For larger machines the phase advancer may be less in capital cost, but there is another point which must be taken into account. If we take a motor with a phase advancer working with a full-load slip of 5 per cent, and assume, for example, that it is necessary to inject 200 kVA of leading current, only 10 kVA will have to be injected by the phase advancer, but the power taken by the phase advancer will be from 1 to 1·5 kW. If condensers were used instead, with a power factor of 0·0016, the power that would be required would amount to only 0·32 kW, or, roughly, one-third of the power that is used by the phase advancer. The actual power loss is small and, therefore, the cost of the extra energy used per annum would probably be compensated for by the smaller capital charge due to the phase advancer. It would be interesting if Prof. Miles Walker could give in his reply any information as to the limit of power of motor below which it is not economical to use phase advancers.

**Mr. J. C. Prescott :** The number of condenser units required to absorb a given amount of lagging kVA is found from the equation $n = P10^9/(\omega c e^2)$, where $P$ = lagging kVA, $c$ = capacity of each condenser unit, and $e$ = working voltage of each condenser unit. Although this would, in general, give the exact number, certain other conditions must be fulfilled for a balanced polyphase load. In the first case, $n$ must be divisible by the number of phases, and, further, the units for each phase must be capable of arrangement in an integral number of lines, each line containing an integral number of units. Thus in the three-phase case shown in Fig. H there must be $I/3ec\omega$ complete lines in parallel, each consisting of $\frac{V}{e}$ units.

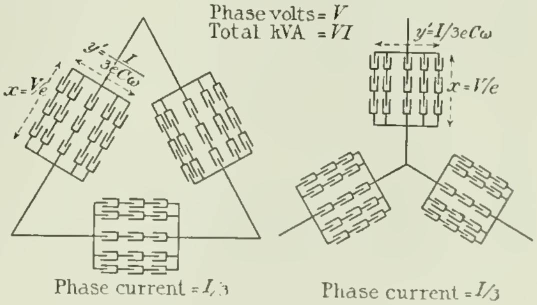


Fig. H.

**Mr. C. Rettie :** The paper apparently deals only with land practice, but the problem is, in many respects, applicable to the electric propulsion of ships, although the conditions of one may be different from those of the other. The first battleship in America fitted with electric drive had squirrel-cage induction motors having two windings on the rotor with high and low resistance, respectively. The efficiency was so low, however, that in the other ships fitted up by the General Electric Co. of America the system was altered, the principle being the same, but a winding on the rotor was introduced with slip-rings to raise the power factor, the winding being cut out when the motors were up to speed. In the later electrically-propelled ships in the merchant marine built in this country and America, synchronous motors have taken the place of the induction motor, on account of the high power factor to be obtained. In a paper * read before the combined meeting of the American Institute of Electrical Engineers and Naval Architects last winter in New York an interesting discussion took place between the author and Mr. W. L. R. Emmet, consulting engineer of the General Electric Company, on this question of power factor. The remarks of Mr. Hollingsworth would apply to land practice but not to the electric propulsion of ships, as a big reserve of power is essential. In a recently published report of a voyage of the U.S.S. "Maryland" (one of the latest American battleships to be fitted with electric drive) it was mentioned that at times, to maintain an average speed of 18 knots for the 7 000 miles covered, rough weather being experienced all the way, 8 000 h.p. above the normal had to be used, The propellers rising out of the water and the sudden loads thrown on the motors show, I think, that the conditions are totally different from those experienced in land practice. Phase advancers have not, up to the present, been used in connection with the electric propulsion of ships, but they were proposed by Mr. W. E. Thau in the paper mentioned above to raise the power factor of induction motors. Synchronous motors, even with induction characteristics, are not suitable for the electric propulsion of ships, except in the case of cargo ships where the question of efficiency does not apply so much as economy. In battleships and large, fast passenger liners where efficiency and control are of the greatest importance, however, the induction motor is the best, provided some means, e.g. phase advancers, could be adopted to raise the power factor.

**Mr. A. E. Malpas:** The paper gives a valuable review of the various methods of improving power factor, and I gather from the various remarks that have been made that, at all events for a moderate-sized installation, the static condenser method is still the best. With this view I agree, although in the future it may be that some of the more modern types of rotary device will become more and more adopted. The average user, however, attaches more importance as a rule to reliability than to the last word in improved power factor. As a user, therefore, I would ask those who are inclined to criticize too severely those of us who put in motors of a rather higher capacity than is absolutely required in normal working, to look at the case occasionally from our point of view. In the case of a large works running a continuous process, wherein one stage of the operations depends on the continuity of the previous stage, it is not permissible to have any avoidable interruptions, and the blowing of the fuses of a motor is, in general, one of the avoidable interruptions. In the case of water pumps, etc., it is easy to arrange the motor with a reasonable margin for safety, but in others it is not so easy, e.g. in haulage gears, furnace drives, etc., where the load may be very variable and a large margin over the ordinary average load must be allowed to cover possible contingencies. In such a works, considerations of power factor take a very minor place, with the result that the average cos $\phi$ may be as low as 0·5, or even less. It is possible for this state of affairs to continue for years until the time arrives when, on account of extensions to process plant, the question of extensions to the electrical generating plant also arises and then it becomes necessary to consider devices for the improvement of power factor. Cases have been known where the expenditure of a comparatively small amount on static condensers has avoided a far larger expenditure on generating plant, but it would obviously be impossible, from capital considerations, to scrap a large number of motors in an existing works merely to substitute others of some of the types mentioned.

**Dr. T. F. Wall:** Professor Miles Walker has shown on page 102 how to deduce the magnitude of the condenser capacity to which the vibrator is equivalent, and it is of some interest to obtain algebraical expressions by means of which the performance of the motor may be calculated for any value of the slip and of the equivalent condenser capacity. These expressions are most easily derived from the equivalent circuit by the use of complex quantities, and I give below the expressions so deduced for the stator current and for the torque. Similar expressions for the other characteristic quantities are easily obtained. The equivalent circuit for an induction motor having a balanced condenser system connected to the rotor slip-rings is given in Fig. J, where $P_1$ volts per phase is the supply pressure; $r_1$ ohms per phase is the stator resistance; $x_1$ ohms per phase is the stator reactance; $x'_{L2}$ ohms per phase is the rotor inductive reactance reduced to the stator number of turns and stator frequency (i.e. the frequency when the rotor is stationary); $x'_{C2}$ ohms per phase is the rotor condenser reactance reduced to the stator number of turns and stator frequency (i.e. the frequency when the rotor is stationary); $r'_2$ ohms per phase is the rotor resistance reduced to the stator number of turns; and $s$ is the rotor slip. Further, assuming a three-phase stator winding, let $u$ be the

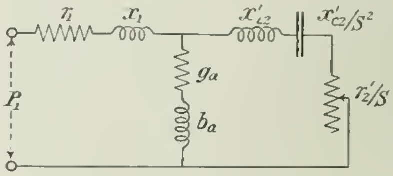


FIG. J.

---

* *Journal of the American Institute of Electrical Engineers*, 1921, vol. 40, pp. 1465 and 1519.

ratio of the number of turns per stator phase to the number of turns per rotor phase. Then for any value of the slip $s$

$$x'_{C2} = u^2 x_{C2} = \frac{u^2}{\omega C_2} \text{ ohms}$$

where $C_2$ farads is the actual value of the condenser capacity in the rotor circuit, and $\omega = 2\pi \times$ (supply frequency).

If $r_2$ ohms per phase is the actual value of the rotor resistance, then

$$r'_2 = u^2 r_2$$

If $x_{L2}$ ohms per phase is the actual value of the rotor inductive reactance at standstill, that is, at the full frequency of supply, then

$$x'_{L2} = u^2 x_{L2}$$

For any value of the slip $s$ the impedance vector of the reduced rotor circuit (Fig. J), is given by

$$Z'_{2s} = \frac{r'_2}{s} + j\left(x'_{L2} - \frac{x'_{C2}}{s^2}\right)$$

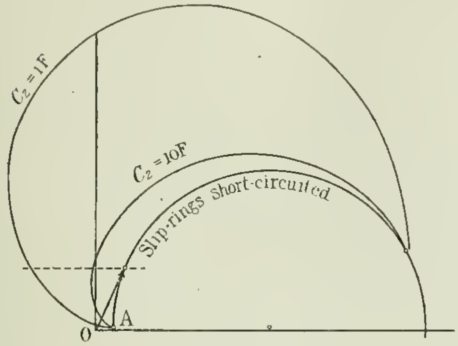


Fig. K.

The vector of the primary current may then be written

$$I_1 = P_1\left[\frac{1 + Y_a Z'_{2s}}{Z_1 + K Z'_{2s}}\right]$$

where $Z_1 = r_1 + jx_1$; $Y_a = g_a - jb_a$; $K = 1 + Y_a Z_1$.

*Example.*—A 50-h.p., 8-pole, three-phase induction motor with star-connected stator is connected to a supply pressure of 500 volts at a frequency of 50 periods. The constants of the machine are as follows:

$r_1 = 0{\cdot}129$ ohm; $x_1 = 0{\cdot}605$ ohm;
$Z_1 = 0{\cdot}129 + j\,0{\cdot}605$; $g_a = 0{\cdot}0038$ mho;
$b_a = 0{\cdot}0476$ mho; $Y_a = 0{\cdot}0038 - j\,0{\cdot}0476$
$r'_2 = 0{\cdot}165$ ohm; $x'_{L2} = 0{\cdot}545$ ohm; $u = 3$;
$K = 1 + Y_a Z_1 = 1{\cdot}029$ (very approximately);

$$Z'_{2s} = \frac{0{\cdot}165}{s} + j\left(0{\cdot}545 - \frac{0{\cdot}0286}{C_2 s^2}\right)$$

where $C_2$ farads is the magnitude of the capacity per phase connected in the rotor circuit. It is thus a simple matter to determine the locus of the primary current vector, $I_1$, for any value of the condenser capacity connected per phase in the rotor circuit. If the rotor slip-rings are short-circuited, this condition corresponds to an infinitely large value for $C_2$, so that $x'_{C2} = 0$, and

$$Z'_{2s} = \frac{0{\cdot}165}{s} + j(0{\cdot}545)$$

The formula for the stator current, $I_1$, then gives the ordinary circle diagram for the short-circuited rotor.*

In Fig. K are shown the current diagrams so obtained for the following three cases, viz.

(i) The rotor slip-rings short-circuited, i.e. $C_2$ indefinitely large.
(ii) A capacity of 10 F per phase connected to the rotor slip-rings, i.e. $C_2 = 10$.
(iii) A capacity of 1 F per phase connected to the rotor slip-rings, i.e. $C_2 = 1$.

It is interesting to note here that if the value of $C_2$ is made very small and eventually becomes zero, the current diagram shrinks to a point, viz. the open-circuit point A. That this is so is apparent from the fact that when $C_2 = 0$ the condition is that of the open-circuited rotor. The torque of the motor is given by the following expression:

$$\frac{3P_1^2(r'_2/s)}{[(r_1+K(r'_2/s)]^2+[x_1+K\{x'_{L2}-(x'_{C2}/s^2)\}]^2} \text{ synchronous watts}\dagger$$

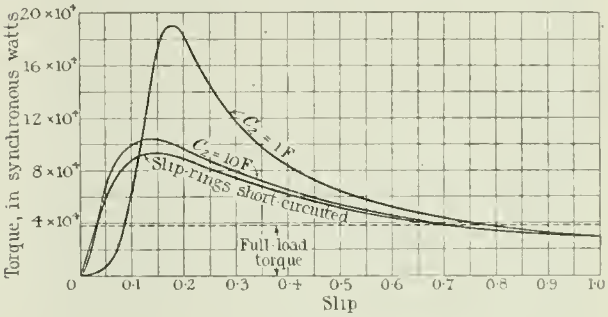


Fig. L.

In Fig. L the values of the torque are plotted for the same three cases as are represented in Fig. K.

[Prof. Miles Walker's reply to the discussion will be found on page 134.]

---

* See E. Arnold: "Die Wechselstromtechnik," vol. 5, part 1, p. 68.

† The definition of the term "torque in synchronous watts" is as follows: the total power given to the rotor is the torque in synchronous watts and is equal to the actual torque on the rotor, multiplied by the angular velocity, in radians per second, of the rotating field. If it is desired to express the torque in pounds-feet units, then

Torque in lb.-ft. $= \frac{0{\cdot}737}{2\pi n_1} \times$ (torque in synchronous watts), where

$n_1$ r.p.s. is the speed of the rotating field.

## NORTH-WESTERN CENTRE, AT MANCHESTER, 28 NOVEMBER, 1922.

**Mr. L. H. A. Carr :** The information contained in the paper clearly falls into two classes. The first deals with the financial question, i.e. how the tariffs should be framed so as to allow for the division of the saving effected by the use of power factor apparatus ; and the second concerns the actual apparatus which can be used for correcting the power factor. The first question—the saving to be effected and how tariffs should be made to meet the point—is one with which I cannot deal adequately ; but I am glad that the author has stressed the point that, as the consumer has to pay for the power-factor-correcting apparatus, the supply authorities must persuade him to use it by making some difference in their tariffs. Some supply authorities do not give any rebate for a better power factor, and it is obviously not economical for the consumer to put in more expensive machines in order to get a better power factor, if he is to derive no benefit from doing so. The question of the improvement of power factor is, therefore, really in the hands of the supply authorities themselves ; if they agree to make a tariff which will give some sort of a fair division of the saving, consumers will introduce the power-factor-correcting machine, but if no advantage is offered they will not do so. There is one type of machine for power factor correction which has been practically ignored in the paper. It is to be regretted that the author has said so little about the ordinary salient-pole synchronous motor with squirrel-cage starting winding. This machine is not described, as are other power-factor-correcting appliances, beyond the single mention on page 97 that one particular firm manufactures this type of machine. Possibly the author thought that it was too well-known to need description, but I suggest that it should be emphasized, particularly as the paper will probably become a classic, that the salient-pole synchronous motor with squirrel-cage damper windings for starting is probably the most widely used machine for power factor correction ; and further, since names of manufacturers have largely been used in the paper, it should be recorded that this type of machine is made by, I believe, all the manufacturers of medium- and large-sized machines in the country. Since something like one-third of the paper deals with the synchronous induction motor, I propose to deal with this subject at some length. In Fig. 4*a* no exciter change-over switch is shown. It was the practice of the old British Westinghouse Company, and is the practice of the present Company, to use a switch, either single-pole or three-pole, to cut the exciter out of circuit when starting up. In fact, Fig. 4*g* shows the standard practice which has been adopted by this firm for many years. At the foot of page 97 the author states that it is modern practice to keep the moment of inertia of a synchronous induction motor as small as possible in order to render synchronization more easy. This point is really of no importance. Investigation shows that the modern synchronous induction motor will synchronize, at full load on 50 periods, against moments of inertia some 50 to 100 times the moment of inertia of the motor itself, with correspondingly greater figures for lower periodicities. The moment of inertia of the load is thus of far more importance than the moment of inertia of the motor. In one case recently where a synchronous induction motor was coupled to a large low-speed mine fan, it was found that at full load the motor would synchronize against a moment of inertia 9·7 times that of the combined fan and motor, while in the case of the high-speed compressors with relatively light flywheels the margin is very much greater. On page 95 the author states that the direct-current excitation on the " star " connection must be $\sqrt{2}$ times as big (in amperes) as the synchronous alternating current per phase for the same copper loss. Referred to the fundamental sine wave of the ampere-turn space curve, which is the useful portion of that curve, the M.M.F.'s due to these two currents are identical. This, however, is not a complete statement of the case, since, if the excitation were fixed at the above figure, the pull-out torque as a synchronous machine would equal the full-load torque, and so the actual direct current applied must be increased. If saturation be neglected, the excitation current will be exactly proportional to the pull-out torque. This means that, under the conditions stated, the exciting current in amperes must be from $2\frac{1}{2}$ to 3 times as great as the asynchronous secondary current at full load. Methods of reducing this ratio by different arrangements of the windings have been discussed elsewhere.* While it is true for the " star " connection that the same M.M.F. is produced for the same copper loss by direct current as by alternating current, it does not always follow that the same copper loss is always accompanied by the same M.M.F. Working again in terms of the fundamental sine wave of the ampere-turn space wave, it is found that with either of the distributions corresponding to the two limiting conditions of three-phase excitation, that is to say, the phase bands carrying currents in either the ratios 1, $\frac{1}{2}$, $\frac{1}{2}$, or 0·866, 0·866, 0, the losses for the same ampere-turn curve are the same. This includes three-phase windings and also the single-phase winding where the correctly spaced two-thirds of the rotor periphery carries the excitation current, the remainder being idle. If the rotor be given a uniform current distribution, however, as in the case of some of the windings illustrated, then, other things being equal, the copper loss for the same ampere-turn wave will be increased by 12 per cent. The " ingenious arrangement " illustrated in Fig. 4*f* is merely the well-known star-delta connection with one leg omitted. With reference to Fig. 8 and similar diagrams in the paper, it should be emphasized that the right-hand circle truly represents the asynchronous operation of the machine only when the exciter is cut out of circuit. It does not represent what really happens when the machine is overloaded and falls out of step as a synchronous machine, as under these circumstances, in addition to the induction motor current shown on the diagram, there is superposed on it a large oscillating current due to the synchronous action of the machine, which causes heavy surges in the line and which persists so long as the exciter remains in circuit.

---

* See, for instance, L. H. A. CARR : " Induction-type Synchronous Motors," *Journal I.E.E.*, 1922, vol. 60, p. 165, and the discussion thereon.

**Mr. S. J. Watson:** The question of power factor correction is daily becoming of greater importance. Some few years ago when three-phase a.c. distribution commenced, it was not of much importance, because mains were not utilized to anything like their full capacity; but as the load increased and the power factor fell, difficulties have been experienced in obtaining the full advantages from the material provided, and anything that can be done to improve the power factor is in the right direction. Those who are engaged in industrial areas know quite well that the main cause of a low power factor on a supply system is the use of motors on a very small percentage of their full-rated duty. This occurrence cannot altogether be provided against, although I think that some improvement in that direction is taking place by grouping machines on a motor instead of utilizing individual drives. In any case the advisability of raising the power factor so as to approach unity is important by reason of the extension of the use of a.c. supplies. Towards the end of the paper the author deals rather fully with the matter of charges and this undoubtedly demands attention, because if money is spent on generating and transmitting a certain kW demand with an assumed power factor, if the power factor is lower than anticipated the capacity of the equipment is reduced, and it is impossible to obtain the income which would otherwise be available. All supply undertakings have not, as yet, adopted a tariff based upon kVA demand, but are still continuing with a charge per kW. Sooner or later some modifications will have to be made to compensate for the money spent which is not being fully utilized. My own view is that there should be one tariff based upon the actual kW demand, and then a somewhat lower figure for the difference between the kW and kVA demanded, because the costs which are incurred in connection with generating a supply, and its transmission, are not all based on kVA. For instance, the costs incurred in connection with boiler-house equipment, prime movers, condensers, etc., depend solely on the kW demand and are quite unaffected by the kVA demand. I do not think, therefore, that one is entitled to charge the same price per kW and per kVA. The fairest way would be to charge, say, £4 or £5 per kW demanded and make a lower charge, say of £3 or £4, for the difference between kW and kVA. Such an arrangement would ensure to the undertaking an adequate income from the money spent, which is the main object of a tariff. Regarding the provision of power-factor-correcting devices, it is perhaps unfortunate that individual pieces of apparatus cannot be made so that they are self-compensating, but in the majority of cases it will be found expedient for the consumers themselves to install the necessary apparatus, and they will be encouraged to adopt this course if the tariff is designed to secure to them an appreciable reduction in their accounts.

**Mr. G. G. L. Preece:** The paper shows how many different pieces of apparatus have been evolved for the purpose of power factor correction; but I should like to ask what is the use of spending time on such apparatus if we cannot persuade the municipal bodies or the power companies to push the matter. The question will certainly lag unless something is done. Municipal engineers have an association of their own. I suggest that some of their members should deal with the subject and formulate some fairly uniform system of charging, coupling with it a simple way of explaining the conditions of power factor correction. It is difficult to get Lancashire mill manufacturers to discuss this question, but if it could be made more thoroughly understood much more apparatus would be used, which of course would be ultimately for the benefit of the power stations. The power companies appear to have considered the subject of power factor correction more than the municipal authorities; probably because they have to look after everything in the way of getting as economical a supply as possible and obtaining the maximum revenue. Until something general is done I am afraid that power factor correction will remain where it is. I recognize that many of the larger municipal stations have seriously considered the question and have given benefits for high power factor, but there are a large number of smaller industrial towns which have done little or nothing. The paper is an important one and I am sure that it will lead to the building of a great deal of additional apparatus.

**Mr. H. C. Lamb:** On page 92 the author states that he is " not aware of any instance where a consumer drawing his supply from a thermic works has put up a rotary condenser on his own premises for power factor improvement." If the Manchester generating stations are " thermic works " then there is an instance where a rotary condenser has been installed on the consumer's premises for the improvement of power factor. That installation was made in 1917. I was much interested to see in the paper the figures given for the Birmingham Corporation power supply. Comparing the Manchester Corporation supply with that of Birmingham, and no doubt other undertakings, I think it is evident that the former is in a very happy position as regards power factor. That is because such a large proportion of the power is converted to direct current. With a load on the a.c. generators of about 80 000 kW one half is converted to direct current. The result is that at times of maximum demand the power factor in Manchester is over 90 per cent. Some of the converting plants have a slightly leading power factor and the remainder of the power supplied as alternating current evidently has a power factor of over 80 per cent, which seems a surprisingly good result. It is quite evident that so far as the Manchester public supply is concerned, the problem of power factor improvement is not so acute as it is with many undertakings, and that perhaps explains the difficulty which is in the mind of Mr. Preece. Probably most municipalities convert a considerable proportion of their power to direct current for traction supply as well as for lighting and power, and it certainly is not the fact that municipal engineers are less keen than company engineers on obtaining the most economical result. The real reason, I think, is that some power companies have no traction supply, and convert practically nothing to direct current, with the consequence that their power factors are often very low indeed. In

Manchester we have recognized the need for encouraging the consumer, and in our agreements with large power consumers there is a clause which gives a rebate and a penalty on high and low power factor, respectively. The author, I think, suggests that the fixed charge should be based on kVA and that that is the only sound system, but there is something to be said on the other side, because it is the continuous power factor and not merely the power factor at the time of maximum demand, that is of importance. It is also stated that some undertakings base their charges on kVA maximum demand instead of kW maximum demand, but I believe that very little has been done in that way. One reason for this is the lack of suitable kVA meters. In the Manchester tariff what has been aimed at has been to give the consumer a rebate on his converted power factor taken over a period, and we have taken a figure of 80 per cent as a standard. The average power factor is obtained by the readings of two single-phase watt-hour meters taken over a monthly or a quarterly period. If the average power factor so obtained is over 80 per cent the consumer is allowed a discount of 0·33 per cent for every 1 per cent improvement, and, similarly, there is a penalty if the power factor falls below 80 per cent. I should be glad if Prof. Walker would say whether, to take the simple example of a consumer with a demand of 1 000 kW and an annual bill of £10 000, if he improved his power factor from 0·8 to 0·95, for which, under the system I have mentioned, he would receive a discount of 5 per cent (that is, £500), that would make it worth his while to install power-factor-correcting apparatus and bear the losses in it.

**Mr. L. Romero** : I should like to associate myself with Mr. Preece's remarks. The information given in the paper as to the practice of various power companies in adjusting their charges to compensate for power factor is of great interest. The systems adopted all seem to be different, and in my opinion none of them is ideal. For instance, the system of charging so much per kVA instead of per kW is unfair, as it makes the low-power-factor consumer pay more than he equitably should, and the high-power-factor consumer less. It is, I think, quite time that the various supply authorities evolved a really equitable system of charging for power factor which could be adopted as a standard all over the country. It is important that any variation in price for variation in power factor should bear as close relation as possible to the actual difference in the cost of supplying. We, in Salford, have devised a system of charging for power factor based as nearly as possible on the actual costs. Our charge for energy is a combined one of so much per kW per annum plus so much per unit, and is subject to advances as the power factor falls below unity. These advances are graded to follow a formula which we have worked out. For example, the variation from unity to 0·9 is less than from 0·9 to 0·8, and so on.

**Mr. G. S. Corlett** : I propose to limit my remarks purely to one class of consumer in whom I am particularly interested, namely, mining plant. While one is, of course, familiar, so far as the general principle goes, with the various methods of improving power factor, in mining plant one has also to consider that all these rotating arrangements for the correction of power factor can only be applied when they are rotating. There are relatively few continuous operations in a colliery except the ventilation, and for many reasons one hesitates about installing synchronous motors for driving a mine fan. What I particularly want to emphasize is this. I am responsible for purchasing current under various types of agreements from public authorities and municipal authorities in different parts of the country, and the different principles of charging may be summarized as a plain flat rate, a differential rate—one rate by day and a lower rate by night and at week-ends—and the rest, by far the greater majority, on a maximum-demand kW-year basis, plus a unit charge. In many of those cases I have taken up the question of a consideration in the consumer's bill for an improvement in power factor, and in one or two instances have been met with a flat refusal. Obviously one cannot recommend a customer to spend any money under those conditions, because he will be in exactly the same position after doing so as he was before. In other cases I have had concessions offered, but the practical financial result has been so small as not to justify any expenditure. I am pleased to hear from Mr. Lamb that in Manchester there is a uniform bonus and penalty for variations up or down from a definite standard power factor. In a case which I had to consider quite recently the proposal was that the power factor was to be taken at 0·8 ; there was to be a very heavy penalty if it fell below this and an almost infinitesimal concession if it was exceeded. For that and other reasons the proposal was not accepted. I have used, with extremely satisfactory results, static condensers on colliery generating plants, and I believe that I installed the first such equipment on 3 000-volt mains. It has worked for many years without trouble or any maintenance costs. A condenser equipment possesses the following advantages, most, if not all, of which are absent in any rotary device : High efficiency ; continuous operation ; can be built in separate sections, which can be located at the points where the low power factor arises ; and, consequently, line losses are reduced and line capacities increased.

**Mr. A. B. Mallinson** : On reading the paper I was impressed with the great advances that have been made since Mr. Carr read his paper last year.* I then ventured to suggest that the supply authorities should give an inducement to customers to install machines which would improve their power factor, and I was rather ridiculed for thinking that such a thing could be done. Another point that occurred to me as an adviser of consumers is this. One may be told : " Get the customer to pay for the improvement device when he is putting his machines in," but are these machines absolutely as reliable as the simple motor which otherwise would be installed ? Particularly is this important when it is borne in mind that almost invariably there will be such a device on the most important drive in the installation, one that will run day and night. If a machine is to be installed that is more or less a box of tricks, and the risk of interruption of supply is thereby run, naturally the customer will hesitate. I was pleased to hear from Mr. Lamb that direct current still has some consideration in electric supply. I think that there is a lot to be said for direct current as against alternating current ; and to hear that Manchester regards the direct-current load as being of great assistance from the point of view of power factor is very refreshing.

---

* *Journal I.E.E.*, 1922, vol. 60, p. 165.

**Mr. G. A. Cheetham :** One speaker has commented on the diversity of charge in connection with power factor tariffs. In my opinion that is, to some extent, due to the difficulty of measuring kVA. If this did not exist there would be more uniformity in the methods of charging. In America a good deal of attention has been given to this subject of measuring kVA, and many wonderful devices have been produced to bring about the desired result. It is possible to get a fair approximation to kVA measurement, provided that the range of power factor change is known to begin with, and much work is being done in that connection at the present time. A customer wants to see a simple dial, to be able to read it in the way in which he read his watt-hour meter, and to compute the bill without using a slide rule. I think something will result from this extension of the range of power factor over which kVA can be measured, and in that event much of the diversity of charging will disappear.

**Mr. V. Mallalieu :** It has been remarked that the paper can be divided into two parts, first the financial and secondly the technical part. In spite of what has been said by the previous speakers the technical side has been quite well taken care of, and the author gives a number of different methods of improving the power factor. The static condenser method does not entail the use of running machinery ; it has been applied to large plants and is absolutely reliable. I agree with Mr. Preece that if the supply authorities will begin to educate the consumer as to the advantages of power factor improvement, and give him a financial benefit, users in turn will buy the apparatus, which can be readily supplied. It is really a move on the part of the supply authorities which is wanted now. Mr. Watson remarked that the cause of bad power factor is largely to be found in underloaded motors and in the use of small motors. That is quite true, but I disagree with him when he advocates the use of larger motors and group driving as against the smaller motors. That is entirely against the trend of present-day practice and future development. The full advantage of electrical transmission is only obtained when the motor is brought up to the machine. In the case of a factory or a works it is no good bringing electricity to the factory and putting in a large motor in the place of a steam engine. The full advantage of electricity can only be obtained by subdividing the driving, and the choice of the size of the motors should be governed by factors such as works organization and the characteristics of the machines that have to be driven. We must give the best service possible for the particular operations involved, and leave the question of power factor improvement to the experts who are capable of dealing with it. I recently saw a curve showing the changes during the last 10 years in the practice in American textile mills in regard to the size of motors. In this curve the average horse-power per motor was plotted against years, and it was astonishing to see how the average horse-power per motor had decreased in that period, the present average size of motor being only about 5 h.p.

**Mr. E. P. Hill :** In connection with the author's remarks on the rotary condenser, there are three 1 250-kVA sets installed on the South Metropolitan supply at Crayford, which are started up by starting motors on the self-synchronizing principle, the starting motor windings being connected in series with the main condenser windings. After the set has pulled into step these motors are short-circuited in the same manner as rotary converters. This considerably reduces the starting kick as compared with tap starting, and avoids the necessity of synchronizing, so that less skilled attention is required, the sets being ready for load in approximately 1 minute from standstill. The beneficial influence of a rotary-converter load upon the power factor of several municipal central stations has been brought out both in the paper and during the discussion, and the importance of this factor in actual practice warrants preferential treatment for the rotary converter over other types of converting plant, the power factor of which is not so good. Although the armature copper loss of a six-phase rotary converter will increase about 30 per cent for a 30 per cent wattless component, this copper loss is only a small part of the total losses in the converter. For example, in a 1 500-kW rotary converter the total loss would be of the order of 65 kW at full load and the armature copper loss at unity power factor, say, 12 kW, which would increase at 30 per cent wattless current to 15·5 kW and, together with the increased field loss, would bring up the total loss to, say, 70 kW, i.e. the total losses have been increased by 7·5 per cent only. The small extra copper required for this amount of wattless component can usually easily be accommodated and is advisable as a safeguard against overloads and improper use in service. A normal rotary converter is, therefore, capable of running with a reasonable amount of leading wattless component without any fear of serious overheating, so that approximately unity power factor can be obtained on the high-tension side of the transformer, the rotary converter taking care of its transformer magnetizing current and the necessary reactance embodied in its transformer for voltage control. If a heavier leading wattless current were required, it might become essential to reduce the d.c. output, but, as has been shown in the paper, most valuable improvement of station power factor is obtained by running at unity power factor or with only a reasonable amount of leading wattless current.

**Mr. E. R. Fry :** The importance of this subject from the supply company's point of view has scarcely been mentioned in this discussion. Loads have been steadily rising and in the case of some power companies it is not a matter of transmission feeders 12 miles long as mentioned by a previous speaker, but more nearly 100 miles. Lighting loads as represented by three-phase low-tension distribution networks have to be fed from the end of these long feeders, and the regulation of the line has to be kept very good indeed. Cases do arise when it is a question whether to lay duplicate lines or to install power-factor-correcting machinery, and I think that the tendency of the large power companies to-day is to adopt the latter alternative and improve the line regulation, rather than incur the expense of duplicate feeders.

## Professor Miles Walker's Reply to the Discussion.

**Professor Miles Walker** (*in reply*): Several of the speakers, including Dr. S. P. Smith and Mr. Ayres, have spoken of the weak points of the synchronous induction motor. It is generally admitted that this type of motor when properly designed does the work required of it in a perfectly satisfactory manner and can be run at unity or a leading power factor. It is of interest to compare the performance of this type with that of an induction motor supplied with a Leblanc phase advancer. First, with regard to overload capacity, it is seen from the locus curve shown in Fig. 13 that the induction motor with a phase advancer can take a much greater overload than a motor having either of the locus curves shown in Fig. 5. One cannot, of course, count the Heyland circle as part of the locus curve of the synchronous induction motor, because the motor is not designed or intended to run on that part of the curve. The torque then is irregular and the power factor very bad. Even if the synchronous induction motor is over-excited so as to take full load at 0·9 power factor, the characteristic is not nearly so desirable in shape as that shown in Fig. 13. Now we have seen that to give the synchronous induction motor a reasonable overload capacity, it is necessary that it shall carry a very great field excitation, and this means more $I^2R$ losses in the rotor than would be necessary in an asynchronous motor when taking normal load. That is one of the reasons why the synchronous induction motor costs more than the plain asynchronous type. In a great number of cases an induction motor fitted with a phase advancer could be built on a smaller frame than is ordinarily employed for a standard motor without phase advancer. This is because the phase advancer makes a little motor stand up to its work and one can safely put in a smaller motor to do the work, provided the average heating due to the load is not going to be too great. When phase advancers come to be made in greater numbers they should not cost much more than the exciters now supplied with the synchronous type. The average load on the phase advancer will be less. As against the slight disadvantage of having three brush arms to the d.c. exciter's two, the average current per brush arm will be considerably less than two-thirds of that required to be collected from the commutator of the d.c. exciter.

The Leblanc phase advancer may be regarded as an exciter in which the current slowly alternates and allows the motor to slip, while the power factor is kept near unity, or leading, as desired. There is practically no difficulty in the commutation, owing to the fact that the current is alternating slowly. In the problem of the commutation of a d.c. generator we must make provision for reversing the current under the brush in 1/1 000 second or less. It adds very little to the difficulty of the problem if the current is alternating at one period per second. The phase advancers which have so far been built commutate perfectly.

When advancers are standardized and manufactured in numbers the price should be very little more than the price of d.c. exciters, and can be partly, if not completely, paid out of the saving in cost of the main motor. The real reason why a very large number of phase advancers have not been sold in this country is that, until recently, very few of the supply companies had made it worth while for the consumer to improve his power factor. Now that concessions on a reasonable scale are being given, consumers are looking around for the best apparatus for the purpose. Where the a.c. motors are small the most convenient apparatus on the market is the static condenser.

Many of those taking part in the discussion have testified to the efficiency of the static condenser for this class of work. For big motors the Leblanc phase advancer contains less material for the same output than the Kapp vibrator, because it can be run at a higher average speed. Moreover, there is only one armature as compared with three armatures, and only one set of brushes per phase is required, instead of two sets. This reduces the brush losses.

As between the phase advancer of the Scherbius type having no field magnet, and one of the type described in the *Journal*, 1913, vol. 50, p. 329, having a field system designed to give an injected electromotive force of any required phase relation to the current, the latter type is much to be preferred in my opinion, for the following reasons.

By giving the injected E.M.F. a slight component in the same direction as the E.M.F. generated in the rotor winding, the slip can be reduced instead of increased, as described on page 101 of the paper. The effect of this is to reduce the size of the phase advancer. Now suppose that the slip of the motor were originally 1·5 per cent, then, taking the figures from page 101, a Scherbius phase advancer in order to inject 250 kVA on the primary side would need to have a capacity of 6·3 kVA if the slip were to be increased to 2·5 per cent. By using a properly designed field system the slip could be reduced to 0·75 per cent, so that the kVA rating of the advancer would fall to about 2·5 kVA. This would mean a much cheaper machine and would give better speed regulation on the induction motor. In the case of high-speed motors the advancers can conveniently be connected direct to the shaft.

When the induction motor has a squirrel-cage rotor it may in some cases be worth while to get the manufacturer of the motor to change the rotor to the slip-ring type having a winding suitable for the phase advancer.

There being very little iron loss in the rotor of an induction motor the temperature-rise is frequently very much smaller than that found in the stator. For this reason there is a tendency to reduce the amount of copper used in the rotor, the slip being increased accordingly.

If we consider the capital cost of the extra copper required to give a low slip, we find that the interest on this and the depreciation amount to very much less than the cost of the power wasted. Even if no advancer were used a rotor should (from the economic point of view) have about twice as much copper as is ordinarily used by the manufacturer, as long as prices of power and copper are as we find them at present. If twice as much copper were to be put into the rotor winding it could carry the magnetizing current with the greatest ease and thus relieve the stator, which is usually very tight in design because provision must be made for high insulation, and for the iron and copper losses.

I do not agree with Mr. Ayres when he says: "It is not economical to correct power factor much beyond unity with phase advancers." The case for the induction motor fitted with phase advancer, and the synchronous induction motor fitted with exciter, are on exactly the same lines except that the heating for an average load is less in the case of the machine with phase advancer. It is mainly a question of whether we shall adopt a.c. or d.c. excitation. The a.c. excitation requires the smaller current at normal load.

As to the economical limit of size of machines to which phase advancers can be attached, my belief is that as soon as engineers awake to the true position, phase advancers will be made and standardized, and though at first they may not be supplied to motors less than about 100 h.p., it will be found that their cost will be so much less than that of static condensers doing the same work, that they will ultimately be used for smaller and still smaller motors until we have phase advancers of only a few watts' capacity.

The advantages of the static condenser for the over-excited induction motor, mentioned by Mr. Dorey, disappear as soon as a.c. excitation is employed.

In reply to Mr. H. D. Wilkinson, I beg to refer him to the following papers:

"The Improvement of Power Factor in Alternating Current Systems," *Journal I.E.E.*, 1908, vol. 42, p. 599.

"Design of Apparatus for the Improvement of Power Factor," *ibid.*, 1913, vol. 50, p. 329.

Many of those taking part in the discussion have spoken of the difficulty of explaining low power factor to their customers. If a charge were made on maximum kVA demand it would be sufficient to have an ammeter and to point out that the kVA is proportional to the reading. If the customer were allowed to watch this, he would soon understand how to operate his plant so as to keep down the maximum demand.

Mr. Edgcumbe's statement corroborates what is said in the paper and also by a number of speakers, viz. that a charge based upon maximum demand in kVA to pay for the capital expenditure, and another charge for kilowatt-hours supplied, constitute not only a simple but also probably as fair a method as any other.

I am glad that Mr. Teago puts the matter in a very simple light showing at once the relation between the various figures in the paper.

Mr. Houghton's comment in extending the theory to a case where an installation is already in being, is of great interest.

In reply to Professor Marchant, it is not possible to fix the limit of power of motors below which it is uneconomical to use a phase advancer. This is purely a question of standardization in manufacture.

The figures that Dr. Wall gives, relating to the condenser depending upon electro-chemical action, are of great interest, and it is hoped that this type of apparatus will soon be upon the market.

In reply to Mr. H. C. Lamb I would say in the first place that a rebate of only 0·33 per cent for each 1 per cent power factor improvement is very small. I presume that it is because Manchester is so well off as to power factor that it cannot afford a bigger rebate. Even with this small allowance it would be worth while for the consumer to install static condensers costing, say, £500 per 100 kVA installed. To improve the power factor from 0·8 to 0·95 in the case quoted would require static condensers having an input of 420 kVA costing, say, £2 100. Taking the interest and depreciation at 10 per cent, this would cost, say, £210 per annum. The losses in the condensers would be about 2 kW, costing, say, £20: total, £230 per annum to be deducted from the £500 rebate. The cost of improving the power factor would depend upon the kind of load and the apparatus available. A very favourable case would be where the whole load consists of new induction motors to be installed. In this case the motors could be built with extra copper in the rotors at an extra cost of £30, and phase advancers of 2 kVA capacity could be provided. Suppose these cost £70; the total capital expenditure would then be £100 (say £10 per annum). The total losses in the induction motors and phase advancers when running at 0·95 power factor would be less than in ordinary motors running at 0·8 power factor. The saving would then be £500, less £10, or £490 per annum.

JIEE 61 (1922-23)

# SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By Professor W. Cramp, D.Sc., Member.

(*Address delivered at* Birmingham, 25*th October*, 1922.)

The story of man's work, individual or collective, is written not alone on parchment in ox gall and black ink, but on warmest human flesh in crimson blood. For every result of human endeavour, be it an Empire, Institution, Industry or smallest touching poem, some human being or beings must, in part at least, have died. This is a universal law, not sufficiently recognized in these days ; that life, vigour, true vitality, can only be transfused—not created. For the realization of an idea a man will die, will give his life—give, I say, not sell. And this life, so given, will vitalize his idea, endow it also with the power of living in exact proportion as the life was given without grudge or reluctance. There is no surer way of discovering to what purpose a man lived than by the answer to the question : For what did he die ? There is no better gauge of the stability and vitality of an institution than the exact tally of human beings prepared to lay down their lives *voluntarily* for its sake. Note how important is the qualifying adverb ! Institutions may, in truth, be fed and maintained by wrongful human sacrifice, as much commercial enterprise has been, and doubtless again will be. But life acquired in this way is temporary, galvanic,—a mere Moloch life, and no true existence at all. To endow work, and the results of work, with true vitality we must give ourselves freely, without money and without price. This is the test of self-sacrifice, of real genuineness and sincerity.

## I. Of a Man.

To the life and work of one who since the end of last session has left us, we need not fear to apply this test. But a few months ago he sat here in characteristic attitude with head bent forward, and keenest scrutinizing gaze ; his piercing eyes half hid beneath the bushy overhanging brows. One look, one word, enough to tell us that here we have to do with a man, an individuality with purposefulness and intention flashing formidable from him. No mere commercial engineer this, we should say, with one eye upon his customer and the other on his pass book ; but a forceful and resolute real-presence, not afraid of declaring that which in the round soul of him he feels to be true. A rugged and even despotic temperament, impatient of triflers, yet having withal that greatest of attributes, sincerity.

He had his hobbies too, this genius ! All the more man for that, I think. Buying a house, adding a music room, living in it for a space, and again moving to repeat his experiment appears to have been one of them. No house was a home to him without a music room, it would seem. Since the invention of his vibrator, no public speech of his could avoid reference to that machine, it was said. Possibly so ; but I will not believe that there was an ulterior and commercial motive in these references,—not if he could not live without a music room. Stratagems and spoils, I think, are not compatible with a music room.

He is gone from us. And so is Kelvin, and S. P. Thompson and John Hopkinson. They made a harmony in their time, this quartette ! Kelvin in the highest soprano flights of physics, dipping ever and anon to indulge in the mezzo of engineering application. Thompson, the suave teacher and melodious alto of the group ; half physicist, half engineer. Hopkinson, with his strong constructive sense, making great engines possible by his grasp of the principles upon which they depended, and Kapp, the engineer, to whom all pure physics was as nothing save in so far as it could be expressed in terms of veritable assemblies of finest materials made to serve the purposes of man. They have gone, I say, these four ; but we still hear their harmonies and may yet read their scores, wherein they have recorded so much of their inner music as they could transmit to us their successors.

In the writings of Kapp we shall, if we search carefully, find the real entity lying behind his character, life and work, to which we may then apply our test of sacrifice. What was it that as a man, and a writer, he was concerned to do ? Did he feel that he had actually and veritably some message from the True and Eternal as yet unwritten ? Let us admit that there is no difficulty in selecting from a man's writings how much he did because the soul in him was longing to express itself, and how much for the publisher's fee. This I find not difficult, even in a case like that of Scott, where the true and the false are most closely intermingled. How much less in the case of Kapp, where true and false are almost synonymous with new and old ! Truly, when a man chooses the written word as his medium, he declares thereby openly to what extent he is a preacher, what gospel or good news he has in him burning to deliver itself, and which must get itself declared, be it at the cost of his very life.

The good news which Kapp preached, as I read it from his writings, was in effect this : That electrical machines could be lifted from the region of the laboratory ; could be designed on principles not very different from, and at least as certain as, those already current among mechanical engineers ; that the formulæ of the physicist, enlightening as they were, could not be left for the engineer in the form of $x$, $y$, and $z$ known or unknown : but that each symbol must to him stand for something of hardest fact, reducible to terms of the dimensions of the apparatus to be constructed.

In Captain Marryatt's novel "Poor Jack," there is a conversation between one of his beloved tars and a French sailor. "I asked him what he called the mizzen-mast," says the English boy, "and he told me the mar-dartymarng. How is it possible to work a ship in such a lingo?" "Quite unpossible," says Ben. Much like this of the poor sailor must have been the attitude of Kapp—himself no great mathematician—when he first tried to "work the ship" from the lingo of the physicists. "Quite unpossible" he found it; no ship could be worked in such a lingo. But that which was not "unpossible" was to interpret the said lingo in terms and language with which the engineer was already familiar. And this he set himself to do with intense and characteristic earnestness. Fully cognizant of the fact that all engineering is a matter of intelligent compromise, we watch him tossing carelessly aside useless mathematical refinements, and seizing with uncanny certainty upon those essentials which lie at the very centre and heart of the matter. "All very well," he seems to say, "for Maxwell and his disciples to express the behaviour of a transformer in terms of $L$ and $M$, but what in stern utilitarian practice must the values of $L$ and $M$ be, and how are these related to the actual number of real cubic inches of metal from which the transformer must in fact be made?" These, and matters like these, were to Kapp the very essence of electrical engineering, and he set himself first to find the essential relationships, then to put them into practice, and finally, by teaching and writing—what I have called preaching the gospel—to hand them on freely and ungrudgingly to whomsoever would listen. He crystallized diaphanous and filmy formulæ into very visible, tangible and robust machines, capable of transmuting day and night the power of many horses into the new manifestation known as electricity; and he showed others how to do the same. This, as I understand it, is engineering and the teaching of engineering. First and last he was, according to my notion, an engineer.

Into the dissemination of this gospel Kapp put all his life and heart, working without stint early and late if so be he might predict more certainly the behaviour of a machine, or elucidate one point to an earnest student. To do this work he wore himself slowly out as the years went by, endowing thereby some of his students, his books and his inventions, with his own life; in virtue of which that part of his work must and will continue to have vitality, vigour and real meaning, for us and for others long after us. He was, as I said, an engineer; more than that—a pioneer—one who, having with whatsoever difficulty cut his little path through a thick jungle, did not hesitate to show it to others.

That the University of Birmingham did not benefit by the best of him as teacher is certain enough; how could it, when he was already 53 years old before he entered upon his career there? But if any would know what he could appear to a student, let them read the words of B. A. Behrend in his work on the "Induction Motor": "To my friend and teacher, Mr. Gisbert Kapp, I inscribe this work," he writes; and again, "the following presentation by Mr. Gisbert Kapp . . . is reprinted from his book . . . because it is the clearest and most concise logical evolution of the principles underlying the theory." And yet again, "it will repay the student to go over Mr. Kapp's presentation of the subject . . . after having become thoroughly familiar with this extract from the work of a master of the art of exposition." This is high praise from an old student. Would that all of us who are teachers or writers might deserve a like encomium.

"His contributions to the Proceedings of the Institution of Electrical Engineers were always highly valued," says Mr. Weekes in the *Electrical Review*. True enough; and his presence among us as a member of this Centre was highly valued also. We do not sit with engineer-pioneers and great teachers every day. Pioneering is apt in every direction to become more and more an exhausted occupation as the years proceed; the widening of the path, and the duty of making the crooked straight and the rough places plain, taking its place. This is the work for us—the successors of Kapp and his like. Let us see to it that it be done with humility, honesty and sincerity, worthy of the best work of the pioneer. And as we do it let us think sometimes of those who, with great labour and many heart-searchings, first trod that way; and let us remember especially him who often met us here without egoism or formality, and to whom to-night we bid a formal adieu, standing for one moment in silence, to mark our respect for his work and his worth.

### II. Of the Institution.

The Institution has become the Chartered Institute. It has for the moment reached the goal of its ambition. All honour to those through whose self-sacrificing labours this result has been achieved! More still; the Institution has achieved popularity with the profession; has become indeed the nucleus and life centre thereof, insomuch that affiliation with it in some degree has become a necessity, and membership of it a hall-mark. There are more than 10 000 members, and the net increase in this great number was for the year nearly 9 per cent.

All this is a very visible indication of life and prosperity, which, with an income of more than £30 000 per annum, has the ability to be a great power and influence in the world if administered with wisdom and judgment, and if continually vitalized by that personal sacrifice of which I have already spoken. But whosoever reads history will find that all great collective endeavours, whether Empires, Industries or Institutions, do, at the very moment when they are greatest, and even because of that greatness, contain the germ of the disease which ultimately leads to their deterioration and decay.

It behoves us, therefore, at this time specially, to search carefully the body politic of our Institution for indications of the presence of any such undesirable microbe. Let us consider whether wisdom and judgment are being exercised in the administration of our affairs, and whether that life-stream of individual sacrifice is being poured unceasingly into the arteries of our undertaking, without which progress will cease and the body begin to waste.

We remark here that Presidents and Councils, not less than Kings and Cabinets, are nominally ministers—servants, that is—and should intrinsically be such, called and chosen on account of their wisdom, to express the best thought and intention of the community, and to carry these into effect. If President and Council do wrong, the responsibility is general, and rests not upon the executive alone. It is for the electors to get the best and wisest elected in whatsoever way they can, and summarily to eject any whose service they discover to be disservice. Moreover, if any man seek office openly or clandestinely, that man is, in my judgment, *ipso facto* unfit for office, as having no proper appreciation of the responsibilities whereunto he is called. Nomination, voting, and the method of election, are therefore serious privileges, far too lightly esteemed among us. No pains are taken by our members generally, to select, nominate, and elect those to whom they wish to entrust their affairs, either in the local committees or in the general Council; nor when the time of voting arrives is the return of voting papers at all representative. Too much trouble, it would seem, is involved in the thinking out of what we wish to get done, how it is to be carried out, and who are the best men among us to get it done. This is not the life-giving spirit of sacrifice. This is the microbe of utter indifference, which has a hold already in us as individual members, and through us is affecting the whole Institution. It is the mild form of a very insidious disease, apparent as one of the prevailing causes of the downfall of many institutions greater than ours. Its root and first manifestation is in the individual member, and with him lies the cure. The Council may do—does in fact—much to stimulate interest in itself and its doings; but this alone will not suffice as a cure—it is only a tonic. It is a question of conscience for each member to see to it that he votes for no man of whom he knows nothing, or of whom it may be said that he acts specifically for some "interest."

That the spirit of life-giving sacrifice is alive in the Institution is, however, apparent from the Annual Report of the Council. Some twenty-five voluntary committees, holding nearly 400 meetings in the year, bear eloquent testimony to this; to say nothing of the forty bodies upon which nominees of the Institution serve. Here is time to the value of thousands of pounds per annum in hard cash given most willingly; and to this not inconsiderable amount much might be added of time given by referees and others in divers unnamed ways.

Yet while thus joyfully admitting such good evidence of life, it is still incumbent on us to ask to what purpose this life is directed, what motive lies behind its manifestations, to be clear in our minds as to the road we are choosing and whither it leads. If we look back over the past twenty years, we find a vast extension of the activities of the Institution. It is a matter of no small interest to con old numbers of the *Journal*, and remark how this and that professor was asked, from time to time, to provide at the eleventh hour a paper or subject for discussion; failing which there would have been no meeting at all. The Institution in those days encouraged and recorded the knowledge of electrical engineering, and did little else. Its activities outside London were negligible. Now, like a huge Briareus, it spreads its hundred arms all over the world, embracing all manner of subjects, from wiring rules to German reparation payments. The growth has passed unmarked, because so gradual. But while thus extending our activities, let us never forget the lofty objects for which the Institution was founded, lest we fall into the position of a mere trade-defence organization. There is need for this warning! Has the Institution any call to deal with German reparation payments, E.P.E.A., and such like semi-political trade-guild work? Politics are no concern of ours, I think, and can only lead to diffusion of energy better employed in other ways; it is but a small step from reparation payments to questions of tariffs. Keep clear of politics, I say. Better, far better, to maintain and extend our original and highly successful expansion, resulting in the system of Local Centres. Has not the real growth and success of the Institution been due to this wise move more than to any other? Listen to the bitter complaints of the provincial members of the Institution of Mechanical Engineers; and remark how they, as well as the Civil Engineers, are being obliged to follow our example in this matter. I can never sufficiently admire the foresight and genius of those who first established our Local Centres.

If, however, in the matter of local devolution we have been able to set the fashion for other Institutions, there still remains the question of their kinship with us, which at the present time fills me with much misgiving. Their number increases alarmingly, and one's list of subscriptions becomes a matter of importance. Besides the three major Institutions, we have the Iron and Steel Institute, the Junior Engineers, the Society of Civil and Mechanical Engineers, the Association of Mining Electrical Engineers, the Faraday Society, the Electrochemical Society, and I know not how many others. Each has its own office and staff, its own *Journal* and meetings and subscription. Curious, too, how a given subject will go the round of them with repetition of discussion *ad nauseam*, and monstrous accumulation of redundant printing. Clearly the matter cannot be left where it is; co-operation or affiliation must be compassed in some manner, or we shall be crushed under the mass of printed stuff waiting to be read.

But how to do it? That is the question. The Institution of Civil Engineers has called a conference on the subject and is apparently in labour. Will it bring forth anything? If not, the Institution of Electrical Engineers should and must take it up, as being concerned in the matter more vitally than any other. But we know the difficulties. Three great Institutions, each with its own palace, and all within one square mile! Did man ever hear the like of it? More than half a million sterling spent by engineers on three piles of bricks and mortar in the neighbourhood of Westminster, and nothing—not so much as would shelter three blind mice—provided in Manchester, or Liverpool, or Leeds, or Sheffield, or Birmingham, or Bristol, or Glasgow, or anywhere where engineers live and move and do verily make engines! All the accommodation put near Westminster, where some plans are indeed made, but virtually no engineering is actually done! Three palaces, I say, three libraries, containing largely the same books, and three secretariats with all their appurtenances and vested interests! Which is going to give way? I confess that I have no panacea to offer as an instantaneous cure for these evils. Nay, more; to put forward cures is not really my business. It is my business to do what in me lies to get intrinsic wisdom on to the Council by means of my vote, and then from time to time, as now, to point out such defects as appear to me to await the attention of intrinsic wisdom. Yet lest my comments should appear to be merely destructive, I will presently put forward with great submission five suggestions as a basis for the better administration of our affairs.

In the meantime, let us lay this to heart, namely, that if we had known our business the situation had never been so bad as it is. We were the last to buy a building, and with us also lies the responsibility for the existence of at least three of the societies that I have named. For consider what might have been done with the £73 000 spent upon our London palace. In 1913, Manchester engineers equipped a whole club for £2 000, paying an annual rental of £600. If in London we had been content to limit our expenditure by a judicious arrangement with one of the other great Institutions, increasing thereby the present wretched load factor on their buildings, there might have existed by now at least an Institution library and reading-room in every important centre in the Kingdom. What a spread of fellowship would this have produced among us; what opportunities for intercourse, exchange of ideas and for reading! Contrast it, if you have imagination enough, with London and its maximum of 1 651 attendances in the library per annum, 5 per day! There would have been nothing like it in the world!

*Comparison of three Institutions*, 1921.

| | Civils | Mechanicals | Electricals | Total |
|---|---|---|---|---|
| | £ | £ | £ | £ |
| Capital expended on land and buildings in London .. | 352 000 | 100 800 | 73 000 | 525 800 |
| Annual subscriptions .. .. .. .. .. | 24 100 | 22 260 | 28 360 | 74 720 |

*Approximate Annual Costs of London Buildings.*

| | Civils | Mechanicals | Electricals | Total |
|---|---|---|---|---|
| | £ | £ | £ | £ |
| Rents, rates and establishment charges .. .. .. | 11 300 | 5 300 | 5 600 | 22 200 |
| Interest on mortgages and loans .. .. .. .. | 1 044 | 1 361 | 1 243 | 3 648 |
| Interest on balance of capital at 5 per cent *less* rents received .. .. .. .. .. .. .. | 15 900 | 3 680 | 1 900 | 21 480 |
| Total .. .. .. .. .. .. .. | £28 244 | £10 341 | £8 743 | £47 328 |

*Interesting Annual Items.*

| | Civils | Mechanicals | Electricals | Total |
|---|---|---|---|---|
| | £ | £ | £ | £ |
| Salaries and wages, 1921 .. .. .. .. .. | 11 000 | 9 450 | 9 400 | 29 850 |
| Salaries and wages, 1914 .. .. .. .. .. | 7 650 | 4 200 | 3 330 | 15 180 |
| Local Centres .. .. .. .. .. .. .. | 940 | 390 | 2 370 | 3 700 |
| Research .. .. .. .. .. .. .. | — | 790 | 218 | 1 008 |

Such a combination of interests might have led, nay might still lead, to other advantages, of which not the least would be the reduction of our annual charges. Our subscriptions amount to £28 000, of which £11 000 is spent upon management. Now to light, heat, and pay the ground rent, rates and taxes, on our London building costs £7 000 per annum, or a quarter of all our subscriptions, without including interest on mortgages and on the capital sum invested. If we add these amounts and allow for the rents received we find that to maintain our dignity and prestige we are content to pay not less than £18 000 every year. Our idea of the value of the papers we receive as shown by the premiums awarded is £208, and our contributions to research amount to £218! Does this indeed represent the relative importance of these items? And are not our colleagues of the other Institutions in a worse case? Look at the table which I have given on page 139, and see whether such a scheme of co-operation as I have suggested ought to be regarded as impossible; ought not rather to be regarded as the one thing necessary, and therefore most possible and urgent; the only way, in fact, to achieve further territorial expansion, and adequately to develop the Students' Sections.

I will not harrow you by attempting a picture of what might have been had the Civil Engineers not been so very uncivil to George Stephenson, nor describe the Great Institution of Engineers that then had been possible. I will not suggest the multifarious activities in which our own Institution might more profitably be engaged; not at least until some of those 25 committees have got their work finished and themselves disbanded. I desire to simplify the issues rather than to make them more complex. There are indeed many suggestions that I might make, but we have reached our conclusions and must conclude.

Here then led me refer to the table containing some comparative data of the three greater Engineering Institutions from which my statements may be checked, wherefrom also some grain of comfort is plainly derivable. For while our capital commitments are seen therein to be the smallest, our income from subscriptions is also seen to be the largest; and while our contributions to local Centres are indeed nothing to boast of, they do amount to nearly twice those of our two sisters taken together. These are signs of grace upon which we are entitled to look hopefully. But far better were it to ignore them altogether than to blind our eyes to the microbes of the diseases which I have diagnosed as existing in our system, and for whose extermination I have now the temerity to put forward the following prescription :—

(1) Whole-hearted devotion on the part of the rank and file to the objects for which the Institution was established; more interest in the discussions, and in the selection and election of representatives on the Committees and Council. It would be well if all would read over the objects, as stated in the Memorandum of Association, at least once a session.

(2) The elimination from our activities of any concern with political or semi-political movements, industrial relationships, or trade-guild propaganda.

(3) The encouragement and extension of the Local Centres, and a more generous treatment of these financially. In particular, the reduction of expenses in London in so far as that is practicable, and the establishment of Institution accommodation and libraries in the provinces.

(4) Encouragement and more generous treatment of the Students' Sections.

(5) Co-operation and, if possible, fusion with other Engineering Institutions, ultimately to form one great English-speaking Institution of Engineers.

# IRISH CENTRE: CHAIRMAN'S ADDRESS

By E. C. HANDCOCK, Member.

(*Address delivered at* DUBLIN, *26th October*, 1922.)

The subject of my Address is: "A Consideration of the Present and Immediate Future of the Irish Centre of the Institution and of the Electrical Industry of Our Country."

I propose first to touch briefly on two developments of engineering interest which have crystallized since our last session, and which may, I hope, be described as being on the border of fact, namely, the advent of two much-talked-of water-power schemes and wireless broadcasting; and then to consider some questions intimately affecting this Centre, and finally the possibilities of an electrical manufacturing industry in our country.

## RIVER BANN SCHEME.

The River Bann will, from present appearances, be the first of our Irish rivers to be harnessed on a substantial scale for the generation of electricity. A strong syndicate has this electrification in hand, and hopes to get a Bill through the Parliament of Northern Ireland in the immediate future. We can be certain that, as soon as the legal path is cleared, no time will be lost in converting this hydraulic energy for the service of the factories, villages and towns along the banks of the Bann.

## RIVER LIFFEY SCHEME.

The harnessing of the Liffey for electric power supply has been a subject of much discussion. This Centre and other engineering societies have discussed its possibilities. It is well known that they have been actively investigated for some time past, and we are now awaiting the final recommendations.

Assuming these recommendations to be favourable, it is to be hoped that the decisions covering the method of finance and control will be taken and published without delay. These decisions will be very important, as they will form a precedent for other schemes. Seeing that the water power is a national resource, I hope that national money resources will, at least to some extent, be applied to its development, giving the principal consumers (in this particular case Dublin Corporation would of course be the largest) an important voice in the control.

It is reasonable to assume that in some 12 to 15 years, after a considerable portion of the capital has been repaid, this scheme could prove a valuable source of revenue to the nation.

I can imagine the control board of this scheme being of further service by forming a common centre where the different electricity supply authorities in the Dublin area might meet and agree to mutually advantageous arrangements for the distribution of electrical power.

## WIRELESS.

Wireless application is at present being hampered by restrictions foreign to its technical side, but it is developing and increasing in vitality out of sight, so that immediately these restrictions are withdrawn it will spring up with just so much the greater vigour. This latest branch of our profession is one that will appeal more perfectly to the community than perhaps any other section of electrical work. It brings with it not only a young and enthusiastic set of men in its service, but also a vast number of the public, anxious to know something of the use of this truly uncanny development. It may be mentioned that the Wireless Exhibition held in London at the beginning of this month was visited by over 25 000 people.

It largely rests with us as to whether we retain a directing control in the formation of the technical rules and regulations in connection with wireless services. To do this we must actively interest ourselves in this new science, co-operate with those specializing in it, help them from our wider experience in electrical matters, and especially give these young men facilities for meetings and papers on their own subject.

I now come to a matter of the utmost importance: How are the recent changes of Government in Ireland going to affect this Centre and our profession? In the following remarks it should be clearly understood that I am referring to the Irish Free State only, and that any suggestions or opinions put forward are of course purely personal.

To try to outline the effect of the change of Government, the steps to be taken in the immediate future, and the general tendency along which this Centre should travel, will necessitate going over matters already well-known to all. It is, however, desirable to re-state our position.

## THE INSTITUTION.

The Institution of Electrical Engineers is rightly called the mother of electrical engineering societies. We belong to the youngest of the professions. Nevertheless, the membership of the Institution is well over 10 000. The standing of its members is acknowledged in every part of the world to be of the highest. This is of exceeding personal importance to all of us, as we electrical engineers in Ireland, as elsewhere, are liable to go abroad.

The record of our Institution is practically that of electricity. Ireland has given it many of its most prominent men, from Lord Kelvin to that of our present President (Mr. F. Gill) who is not only a Dublin man but also one of the original members of this Centre.

The Standard Rules accepted throughout our country for electrical work are those of this Institution. The development of our profession is so rapid, and improvements take place so quickly, that the Institution has had to form many standing Committees for the effective control of these developments. Their results and records will be of inestimable value to us.

### IRISH CENTRE.

The Irish Centre consists, for all practical purposes, of the electrical engineers of experience and authority in Ireland. It comprises electrical engineers of all branches of electrical work except one (at least as far as the Irish Free State is concerned), and that one is the industrial or manufacturing side. Our number is small, being 148 for the whole of Ireland, but I venture to say that no similar number of men in Ireland have the control of such power, literally and figuratively, in their hands. The community rely on this small body of men for its supply of electricity for lighting, industrial power, tramways, telephones, telegraphs, railway signalling, etc.; in fact there is not a profession or trade that is not in a major or minor degree applying electricity to its service.

I say that it is a good thing for the community that we have a due sense of our responsibility.

There are one or two points that it is desirable to touch on for the welfare of this Centre. The first is the question of a home and an address. At present we have no home. I should be satisfied if we had one room of any kind for the housing of our library, and I am quite confident that with a place to keep our possessions, those possessions would grow. Having a room we could build up that very desirable thing, a good up-to-date reference library.

This question is also of importance to our Graduates and Students. We are anxious to increase the number of these and they would feel more at home and free from restraint when meeting in a room belonging to the Institution.

It is very desirable that all electrical engineering students in our technical colleges should know the advantages of belonging to the Institution. They should automatically join as Students when starting the last year of their college courses. The younger men ought to understand that in a few years' time they will not be accepted as qualified electrical engineers unless they belong to the Institution, any more than a man is accepted as a chartered accountant unless he has qualified and passed the examinations of his Association.

I should also like to say a few words with regard to Associates. It is not sufficiently well known among the public that an Associate of the Institution, by the mere fact of being an Associate, admits that he is not a professional electrical engineer. This class is created for, and open to, all members of other professions whose admission would conduce to the interests of the Institution. I cannot help feeling that there are many men eminent in other professions in Ireland whose admission would be mutually advantageous.

On the one hand we should learn from them their very specialized applications of electricity, and, on the other hand, once we knew their exact requirements we could lay ourselves out to give them perhaps something better in the way of electrical apparatus than they have at present. Contact is, however, necessary.

### EFFECT OF CHANGE OF GOVERNMENT.

Having dealt with these minor but important matters I come to the broad question as to how the change of Government is going to affect this Centre and our profession as a whole.

To begin with, it is necessary to realize clearly that we are, and shall be for some time, carrying on with electrical rules, regulations and laws more or less in a state of suspense. This means, as I see it, that our existing rules are replaced by blank sheets of paper. *Inter alia* I would remark that in the past we have accepted all these various rules, regulations and laws controlling our profession, which others have provided for us, without, I fear, any appreciation of the labour and trouble that the compilation of these has meant.

Now, bluntly, the question is whether we are going to help to rewrite those blank pages. There are two paths open to the Irish Centre :—

One, that of apathy, allowing others to accept the responsibility. If we remain apathetic, can we expect to be taken seriously if we protest against any technical rules or regulations of which we disapprove ?

The second, and to me the only possible path, will be to accept manfully our responsibility and, further, to make it clear to all concerned that our members interested cannot reasonably be expected to carry out and be responsible for the application of technical rules and regulations governing our profession unless the Irish Centre has a voice in their framing.

I pointed out before that we had a sense of responsibility to the community, but at the same time we are aware of our value as well as our duty.

Responsibility reflects responsibility. Accordingly, those acting for the community will no doubt realize their responsibility to our profession and appreciate the advantage of having in existence the Irish Centre of this Institution to co-operate with in the re-affirming, revising, or recasting of our highly technical rules and regulations, making them, where necessary, more suitable to our local requirements. My remarks are purely personal, but I have no hesitation in affirming that if and when called upon by those in authority to do this work, this Centre will give of its best for this duty.

It will be absolutely necessary for us to rise to this opportunity, for which we shall require all the experience, foresight, and wisdom possible.

It means the framing of rules and regulations affecting generations to come. It will be of the utmost importance not to fall into the mistakes made by other countries in making the framework of their rules too rigid. The framework must be made so as to be adjustable from time to time, to give flexible control, regulation and standardization. In this connection I would point out one very important point where the future will be very different from the past, and the sooner it is appreciated by all concerned the better. Regulations will have to be lived up to. For instance, there will be no more self-constituted electric supply authorities without authority.

The change of Government is, in my opinion, going to be beneficial to this Centre in the ratio that we accept responsibility, and work, and use our influence for the good of our profession and the community.

Before leaving this subject, and in the hope that these few words may reach the proper quarter, I repeat the great desirability, nay necessity, for a definite understanding between this Centre and the Government Department responsible for the making of technical regulations governing the generation and supply of electricity, or in connection with electrical apparatus.

### Electrical Manufacturing in Ireland.

The other question with which I wish to deal to-night is one on which I feel strongly. It is that of the possibility of electrical manufacture in the Irish Free State. After writing that last sentence I sat and looked at its grotesqueness. A country with 3¼ million inhabitants, setting up its own Government with an Army and other Government Departments, and yet I have to write "possibility of manufacturing" in regard to the most necessary and vital, most progressive and most rapidly developing of all industries. Yet it is perfectly true; for, with the possible exception of one small company, I know of nobody attempting electrical manufacture in this country.

This is a most unhealthy state of affairs, not only for our profession but also for the country. It is an explanation of the meagreness of our membership as a whole, and especially of our Graduate and Student sections.

What is the reason for this state of affairs? I have often asked this question but have never got a satisfactory reply, so I am quite certain that I shall not satisfy you by a definite statement.

I shall, however, treat it indirectly by asking if we electrical engineers have used our influence to create an electrical industry. We, who are familiar with electrical apparatus and know that it is not so difficult to manufacture or so mysterious as the public may think, have we endeavoured to interest capital? Or have we taken up the attitude that it is impossible to make anything in Ireland?

I definitely maintain that those of us who are in a position to influence the investing of capital in our profession should do so, in addition to giving all possible support to a home industry, contingent on that industry showing that it is seriously endeavouring not to obtain a high price for an inferior article. It is regrettable that many people have taken up the attitude that we are unable to manufacture. The very first thing necessary is to get rid of that frame of mind. It does not matter how small the article is to start with, but let people get interested in production and the good work would go on.

Another frequent answer is that there is not the demand in this country. There is not, of course the demand for the production of turbo-alternators and large machines, but there are some 3¼ millions of people in the Irish Free State, and if the home market alone cannot support a reasonably good electrical manufacturing industry, then this is only due to some artificial cause which must be got rid of. But there is no such reason.

Let us take some other European countries. The population of Denmark is 2¾ millions, Norway 2½, Switzerland 3¼, and, as is well known, those countries manufacture electrical apparatus extensively, not only for their own purposes but actually to export a considerable quantity.

Canada is in a very similar condition to ours, in that she is next door to a country with immense production facilities, a country continually looking out for markets for her products. In 1904 the population of Canada was 5½ millions. I take that date, partly because her population was much smaller than at present, and partly because I had an opportunity to see some of her electrical facilities.

At that time the Canadian General Electric Company had a factory occupying 40 acres, where they turned out practically everything electrical. The Canadian Westinghouse Company had a similar organization, and in addition there were numerous small factories, all forming a young and vitally alive industry.

The High Commissioner for the Commonwealth of Australia has kindly sent me the following particulars of what is being done there.

Number of Manufacturers of Electrical Apparatus.

| | New South Wales | Victoria | South Australia | Western Australia | Queensland | Tasmania |
|---|---|---|---|---|---|---|
| Population (1911) .. .. | 1 650 000 | 1 315 000 | 408 000 | 282 000 | 605 000 | 191 000 |
| Motors .. .. .. .. | 12 | 18 | 1 | 2 | — | — |
| Starters .. .. .. .. | 8 | 8 | 1 | — | — | — |
| Switchboards .. .. .. | 17 | 15 | 1 | — | 4 | — |
| Switchgear .. .. .. | 7 | 3 | — | — | — | — |
| Transformers .. .. .. | 3 | 10 | — | — | — | — |
| Travelling cranes .. .. .. | 3 | 1 | — | — | — | — |
| Instruments .. .. .. | 8 | 7 | — | — | — | — |
| Machinery .. .. .. .. | 4 | 5 | — | 1 | — | — |
| Fittings .. .. .. .. | 14 | 13 | 1 | 2 | 1 | 1 |

These figures taken in proportion to the population show what can be done. Compare them with the Irish Free State.

The change of Government is going to give a strong inducement that was previously absent. Government Departments are now in a position to place contracts at home for quantities which will ensure a manufacturer having a reasonable and continuous output from the start. This will enable him to produce at reasonable prices whilst developing his business along the usual trade channels.

Without such contracts it is difficult to face competition with manufacturers already established and holding such contracts from their own Governments.

When speaking of electrical manufacturing it should not be overlooked that it is in a very large degree mechanical work, and work that a number of our well-equipped mechanical workshops in Dublin could undertake if they would only look into it and add an electrical engineer to their staff to ensure that the design and finished product were in accordance with electrical requirements.

### PATENTS.

The question of patents is a delicate one. It will, however, be disappointing if the practice of other countries is not followed in making it necessary for patentees to manufacture in our country in order to retain their privileges. In this connection it might be worth while putting forward a suggestion as to the possibility of eventually establishing a permanent Inventions Bureau following the practice of Great Britain during the European War.

### RESEARCH.

This automatically brings me to the question of research work. Important developments are sometimes the result of a "brain wave" but more generally are the cumulative effect of patient research work. Research work costs money, and the only method by which it can be undertaken is by Government aid, or where huge trusts or combines are in such a strong financial position that they can put on one side an allowance for this work. Having no electrical manufacturers, much less combines, the only alternative is Government aid.

Dr. Eyre, Director of the Linen Research Institute installed outside Belfast, has kindly sent me particulars of this Institute and its method of support.

It fits into the comprehensive scheme that each industry is made responsible for its own research work. The different companies subscribe annually an amount corresponding to their capital. For example, in the linen industry a company with a capital of £17 000 subscribes £10; from £17 000 to £26 000 the subscription is £15, and so on, the Government voting a grant which is allocated pro rata on the amount contributed by the industry. This is an admirable scheme but impracticable for us. I would suggest that there should be a laboratory capable of research work at each of our electrical engineering technical colleges. Further, that one of the staff in each college should be appointed on account of his outstanding merit on research work. The results of such work should be given to our own manufacturers in the first instance. Where such results were patentable the resulting fees (due allowances being made to the inventor) should in due time help to support this work.

What I call "educational engineers" might be termed "manufacturers" from one point of view, in that they are taking raw material (our young manhood), representing the most vital part of the capital of the country, increasing its value by a technical training, and then exporting it abroad, for the simple reason that we have no electrical industry to absorb our young electrical engineers.

### TECHNICAL EDUCATION.

The apparent situation is that tens of thousands of pounds of national money is annually expended in our technical colleges, covering the first definite step in the education of our young electrical engineers, and for the second and nationally more important step of consolidating their college training in a manufacturing works neither national nor private capital has expended a penny. This second step is nationally more important, as in order to get this experience these young men leave the country and seldom return. If one-tenth of this money had been available for commerical enterprise it would not be a case of writing as to the possibility of an electrical industry.

Do not think that I would wish to suggest the reduction of the grants for technical education. The remedy does not lie in this, but in creating and developing work at home so that those young men can make a livelihood and devote their energies to their profession without going abroad, and I hope that in the near future this will be possible.

The term "educational engineers" has been used in order to get away from the more academical term of "professor." Our educational engineers should not have the idea that they are simply responsible for getting into the heads of their students sufficient knowledge of a technical nature to enable a reasonable percentage of them to pass their final examinations. Those in charge of our colleges should remember that they are part of the electrical industry of this country and that they are in their positions for the sole purpose of furthering the interests of this industry as a whole. It is true that their primary concern is to educate our young manhood, but it is also important for them to keep in contact with the operating side of their profession, placing themselves and their laboratories at the service of the industry. This would automatically mean that they could place their students along lines of maximum efficiency.

This Centre is common ground for all the branches of our profession. It would be gratifying to see it made use of by the interested parties for the purpose of bringing about a research arrangement as outlined above, and for bringing our technical colleges into more intimate relation with our electrical industries in the future.

We are a relatively small community, and are at a most critical period in our economic development. We are starting peculiarly free from precedent and vested rights. This is a combination that, given team work, makes for efficiency. In the past we have allowed our individuality to overrun our team work, hence our more or less watertight compartments.

### Co-operation.

It is most desirable that everybody interested in electricity, whether he be an electrical engineer, a member of the Government, or a shareholder in a village electric lighting company, should co-operate through his respective association or institution so that electrical engineering, acting as a living whole, may most efficiently play the part in building up our country that it has in others. This part is of the greatest national importance, entering into the health and well-being, industrial and physical, of the community as a whole.

If my remarks to-night have had any effect in bringing home to this Centre our responsibilities in the immediate future, I shall be satisfied. At the same time I sincerely trust that some of the suggestions put forward will be such as to stimulate thought.

In conclusion, I hope that the vigour of this Centre, which has steadily increased under the energetic and capable direction of our last three Chairmen, Messrs. R. Tanham, A. G. Bruty, and R. N. Eaton, will be made full use of for the control, development and efficiency of that most vital, rapidly growing, and important profession to our country, the profession of electrical engineering.

---

# NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By A. S. Barnard, Member.

(*Address delivered at* Manchester, *14th November,* 1922.)

I should first like to draw attention to the step taken last year, largely on the initiative of our new Hon. Secretary, Mr. A. B. Mallinson, and Mr. W. A. Coates, in the inauguration of Informal Meetings. From these meetings the reporter is rigorously excluded, and, judging by the success attained last year, I think we may look forward to their proving a most useful and interesting feature of the present session.

The range of activities covered by our membership is now so extraordinarily diverse that there are a host of comparatively small matters—which might be called side-lines of electrical engineering—which are of interest to members, but which very possibly do not warrant the devotion of a whole evening's debate to the one subject. The informal meeting affords an opportunity for arranging short discussions to deal briefly with two or three such subjects at one meeting.

When it is remembered that electrical engineering in its widest sense has now a foothold in almost every human activity, it becomes obvious that, important as are the questions of cheap generation and distribution of electricity, these are not the only matters which the Institution must consider, or in which alone it will be looked to by its members for guidance. For example, in the electrical equipment of ships, or of railway rolling stock; the use of electricity in surgery and therapeutics; electricity in mining, agriculture, textile mills, or chemical industries; and wireless telegraphy and telephony, there are very many members of the Institution who are interested and who could interest us in these and similar applications of electrical engineering. I should like to see some of our informal meetings devoted to discussions not only on theory and design, but also on a working experience in many of the lesser side-lines of electrical engineering.

I propose to deal very briefly with some of these minor subjects which I have described as side-lines.

Why is it that we still have gas-lighted passenger trains in Great Britain? Have we as an Institution ever taken any steps to develop the use of electricity in this direction? Surely there have been sufficient examples of the danger to life from gas-lighted coaches to afford us a text for a strenuous campaign in favour of the only safe illuminant. Train lighting by electricity remains, however, a comparative side-line in the hands of a few, and, so far as I am aware, it is not even necessarily installed in the new rolling stock built to-day. The obvious advantage of being able to light up a train as it enters a tunnel is so frequently exemplified in the police courts that one wonders why it is not made compulsory.

The subjects of wiring for power in works and factories, and the kindred one of domestic electric lighting, must receive attention at the hands of the Institution if we are really concerned in the development of the industry on the right lines. The final authority in these matters is the consumer who pays the bill. If wiring is made too expensive by elaborate specifications and regulations, less wiring will be done, for the consumer will object to the cost. If on the other hand we tolerate inefficient and shoddy wiring, there will be little use in building super-power stations and offering cheap current to a man who experiences trouble and expense through the inefficiency of the installation on his own premises. The wiring contractors are probably in more direct touch with the consumer than any other members of the electrical industry, and for that reason, if for no other, they have a big responsibility in the matter of wiring practice. They will help themselves and the whole industry if they will discuss their difficulties and troubles with the Institution as freely as do plant manufacturers and central station engineers.

This session will, I hope, see some attention paid to the important work that is being done by the electrical engineer in the collieries. My earliest experience of electrical work was gained in the collieries of South Wales, and I still remember the joy of switching on new lights underground, or starting up a motor-driven pump by the light of a Davy lamp. I am afraid that the immunity from electrical disaster of those early installations must be ascribed to something else than the excellence of the work which we carried out, or of the machinery we installed, for I have recollections of old Gramme machines with open (and by no means sparkless) commutators, and cables, switches and accessories that would prove an endless source of worry to the present-day mining engineer. Electricity in mines has now gone far beyond the experimental stage, but I am sure that there are yet many problems of great interest which could with advantage be discussed by this Institution—problems ranging from the heavy engineering of haulage and winding to the relatively small but important question of the design of a miner's portable lamp.

Electricity in agriculture is a side-line which perhaps may not be expected to be of particular interest to this Centre, though it is conceivable that if we devoted more attention to the subject of smoke abatement we might develop a more personal interest in this very fascinating application of electricity. As things are, the smoke-clouds of Manchester and the neighbouring towns are responsible for a tremendous waste of energy on the part of farmers and gardeners who plant hopefully, and reap occasionally. When we reach the All-Electric Age, and when open domestic fireplaces and smoke-making locomotives are things of the past, we may hope for a great improvement in agriculture.

There is one branch of agriculture largely practised in our area which seems to me to offer a promising field for research. If we could devise an electrical treatment of seed-potatoes that would render the crop immune from wart disease, we should confer an immense boon on the potato growers of Lancashire, and earn the gratitude of thousands of allotment holders. You may say that this is not electrical engineering, but I claim that it is a proper matter for consideration by electrical engineers, and I need only point to the results obtained in Herefordshire through interesting the farmers in electricity, to show what a bearing these side-lines can have on the larger problems of public electricity supply.

We in this country are too prone to leave it to others to show us what can be done. We established electricity supply stations to supply electric light. The supply of current for power purposes was an experiment, and, in the view of very many people, not too hopeful a one. Electric trams were said to be working successfully in America, and gradually we learned to tolerate the overhead trolley wires in our cities. Are we to wait until the whole of the American railways are electrified before we really tackle the problem of main-line electrification in Great Britain ? We know that the electrification of the railways will benefit the nation ; we know that sooner or later it will be carried out ; surely, therefore, we should educate public opinion in the matter, and make the advantages so clear to the ordinary traveller by train that he will insist on the electrification of railways. I think there can be no doubt that the matter would advance more rapidly if the electrical engineers of this country would make a decided and authoritative pronouncement as to what should be the system to be adopted ultimately throughout the main lines of the British railways. I think also that the Electrical Development Association might usefully devote some of its energy and resources to cultivating public opinion and creating a more insistent demand for this reform.

Legitimate advertising and publicity are forces which we can no longer ignore, and the work of the Electrical Development Association is a side-line which will require more and more attention at the hands of the Institution.

I look upon the storage-battery industry in which I spend my time as being another of these side-lines. There was a time when the central station for the supply of electricity in a town consisted of one, two or three direct-current generators, driven by vertical steam engines, usually of the high-speed, single-acting type. In those days the storage battery was an essential part of the scheme, making for economy by enabling the running plant to be shut down for several hours in the night, and even over the whole of the week-end. These early installations have been scrapped or superseded as the growth of the industry called for larger and more economical generating stations, and as the turbo-alternator was developed to meet that demand. In many instances, however, the original direct-current station has left a legacy in the form of a direct-current network of mains, to which are connected large numbers of consuming devices and installations designed for direct current alone. It happens, therefore that in many of our larger cities the densely loaded d.c. network survives in the heart of the important business area, whilst the outer manufacturing or residential areas are supplied by a.c. distributing mains. This, of course, leads to some complications and a measure of inefficiency, and the question arises as to whether there is any justification for the survival of these large d.c. networks. My own opinion is that a plebiscite of consumers would show an overwhelming majority of power users in favour of a.c. supply, but an equally overwhelming majority of private users, shopkeepers and residents, who would favour direct current. The exact reasons for this preference would take too long to discuss, but one of the justifications can be found in the possibility with direct current of holding a little in reserve in a way which is practically impossible with alternating current, depending as it does on running machinery and a constant supply of labour and fuel in the boiler house.

It is easy to ridicule the idea of using storage batteries to deal with the immense loads on the mains in a city like Manchester or Birmingham in the event of a complete breakdown of the generating plant. It may be said that this risk is insured against by linking up with adjacent supply undertakings, and I grant that this does give a very real safeguard to the continuity of supply. At the same time, it must be remembered that the conditions which are temporarily upsetting the plant may be affecting other supply stations also. The fact remains that a few thousand kilowatts in a storage battery at a substation, instantly available and under direct control, may easily convert what would have been a serious interruption or curtailment of supply, into a slight irregularity which would pass unnoticed by the majority of consumers.

A year or two ago, when both labour and fuel conditions were at their worst, the peak-load supply apparently became a nightly difficulty in more than one large electricity undertaking. I was somewhat surprised to see how calmly the consumers accepted the dictum of the engineers and committees that the supply would be curtailed or restricted between certain hours, or as regards certain classes of consumer. Of course there are commercial limits to the value of storage, but I cannot help thinking that in the past some of the failures to meet obligations to the consumer have been due to an over-zeal for economy, rather than to that hoary scapegoat "The act of God." And what supply authority has really tested the commercial possibilities of storage ?

When one examines the comparative statistics given in the *Electrical Times* and sees how very few of the public supply systems are working with a load factor of more than 25 per cent, one wonders what would be the effect on the average cost per unit if the load factor were brought up to unity, or even to 50 or 60 per cent. The figures of one large station are as follows :

| | |
|---|---|
| Total units sold .. .. | 137 000 000 |
| Maximum demand .. .. | 67 100 kW |
| Load factor .. .. .. | 23·29 per cent |
| Total works cost .. .. | 1·73d. per unit. |

Is it not conceivable that with a really comprehensive system of storage, for example a system that would bring this load factor up to 50 or 60 per cent, the works cost could be brought down to 1·23d. per unit, with a gross saving of 137 000 000 half-pence per annum or, in round figures, £250 000 per annum ? The maximum load of 67 000 kW may be regarded as plant having a capacity of 32 000 kW running at 50 per cent load factor, and a further 35 000 kW capacity running idle all the time. Storage that could take charge of 35 000 kW for, say, two hours per day would, in all probability, be amply sufficient to ensure that the running plant necessary to meet the maximum demand would work year in and year out at a load factor of 50 instead of 23·29 per cent. Battery substations to provide this storage would cost, so far as I have been able to ascertain, somewhere about £1 000 000, and there would be a problematical £250 000 per annum to pay for the capital and working expenses. I know that the idea will be scouted, but I submit that the question of storage is not generally treated seriously enough, or looked at with a sufficiently large and wide vision. A reserve of energy of 35 000 kW for two hours, or nearly 55 000 kW for one hour, is a consideration not to be ridiculed, even if the million-pound capital expenditure is a big sum, and even if the battery losses and maintenance costs would account for a large proportion of the £250 000 per annum that I have suggested might be saved by an improved load factor.

We have had in the past some very useful discussions on the subject of specifications and the work of the consulting electrical engineer, but I do not think that the last word has yet been said on that matter. The difficulty of drawing a specification which shall define while it does not exclude, seems to be insuperable, and is only equalled by the difficulty experienced by the contractor in gauging the exact percentage of deviation from the "letter" that will be accepted as still being in accordance with the "spirit" of the engineer's requirements. So long as the system of competitive tenders survives, the contractor is haunted by the knowledge that the quotation which, on being first read, shows the lowest figure as the "contract sum" has secured a psychological advantage over all others. Close investigation will often show that this is not really the cheapest tender, but the first impression has been created, and it requires an effort on the part of the consulting engineer to clear that impression away and secure equal consideration for the remaining tenders. Under these circumstances it is not surprising if, in tendering for, say, a ship, the contractor is tempted to omit the tar and thereby reduce his tender to a figure lower than his competitors'.

It is my conviction that the high standard of engineering work attained in our municipal power stations has been reached in spite of, and certainly not because of, our system of public invitation to tender ; and now that there is a certain amount of standardization in prices for standard work, it calls not for less, but for greater care on the part of the consulting engineer to secure that his client shall obtain the best bargain.

Another matter which I think concerns us as an Institution, is the qualification of the electrical contractor who carries out the installation work in our houses and factories. I am well aware that this work of wiring is hedged around with regulations and rules, and quite frequently is inspected on behalf of a supply authority or insurance company. For all that, it is obvious that a certain amount of shoddy work is still being done, and shoddy work in wiring brings discredit on the electric lighting industry, and thereby on the whole electrical profession, more quickly almost than any other factor. I feel that until we evolve some system of national registration of electrical engineers we shall continue to expose a very vulnerable point in our armour to the attacks of those who work for immediate returns in hard cash, without regard to the effect of their work on the industry as a whole. Any such system would have to include the registration of master contractors as well as of wiremen and electrical mechanics. Were it merely a question of workmanship on the part of the wireman the matter might safely be left to the trade unions concerned and it would gradually right itself, but scamped work is as liable to originate in the office as it is to occur on the actual job. Furthermore, it is common knowledge that the electrical contractor is often the customer's sole adviser and consultant, and when it is remembered how largely electrical engineering is judged by the reliability of the light in the living room, it can be appreciated how much we, as an Institution, are concerned in the status of the wiring contractor.

I think that the electricity supply industry is to be congratulated on the thorough-going manner in which it has adopted the scheme of Whitley Councils. I am sure that this scheme will go a very long way towards stabilizing and consolidating the labour in this industry, where stability and continuity of service are matters of great value. I know from experience that the works committee can be a powerful agent for good in a factory, and I feel sure that the results that can be obtained by the open discussion of difficulties will be none the less marked in a supply undertaking. Certainly the managerial representatives on a works committee such as that in the factory with which I am associated find the time well spent, if it is only in their own education. I would urge employers of labour to trust the works committee more and more, remembering that responsibility begets a sense of responsibility, and trust engenders loyalty.

This principle might with advantage be extended in other directions and applied to the relations between buyers and consulting engineers on the one hand, and manufacturers and contractors on the other. I should say that the surest way to get scamped work from a contractor or manufacturer would be to let him think that you expected it. Treat him honourably, and expect him to treat you so, and the chances are that you will not be disappointed. In other words, when you are treated as a gentleman, you instinctively try to behave like one.

Our War Memorials have another function to which I should like to allude very briefly. They serve to emphasize our dependence on each other, and the uncertainty of accomplishment of our individual plans. In a large Institution such as ours there are inevitably many members whose plans will be upset and who will fall by the wayside. We are all aware of this, but I think we do not all fully appreciate the significance of the facts in relation to ourselves. If we did I feel that there would be a greater response to the appeal for regular annual subscriptions to the Institution Benevolent Fund, the only limitation to which at present is the fact that its power for good is at present limited only by the inadequacy of its material resources.

In conclusion I wish to direct your attention to an event which I hope will be a source of great pleasure to us all. In June next the Institution will visit the North-Western Centre for its Summer Meeting. Friends from all over the country will be coming to see what we have to show them of electrical and scientific interest, and it will be our very pleasant duty to make their visit as enjoyable as possible. As a Centre embracing Manchester, Liverpool and North Wales we have unrivalled opportunities, and your Committee is determined to make the occasion a memorable one. I am sure that in so doing we shall have the whole-hearted support of every member of this Centre.

# SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By A. S. Hampton, Member.

## THE ECONOMIC ASPECT OF RAILWAY ELECTRIFICATION.

(*Address delivered at* Glasgow, *14th November*, 1922.)

Experience gained steadily confirms the high value of the results obtained from the electrification of suitable railway sections, and but for the present financial difficulties there would be considerable activity in the extension of this class of working.

So far no movement with regard to electrification has taken place in Scotland, and if reference is made to the map of England it will be noticed that at every point where electrification has been adopted there is density of population and a consequent density of passenger traffic.

With the exception of Glasgow and the Clyde Valley area there is nothing like the same density of passenger traffic in any part of Scotland as obtains in England, and in the evidence given before the National Wages Board in connection with the case for a reduction in railwaymen's wages it was stated that for every mile of railway in England 77 777 pasengers were carried, as against 33 675 for every mile of railway in Scotland, but these figures only in a measure account for the slow movement in the direction of electrification on the part of Scottish railway management.

There was the difficulty of obtaining reliable figures as to the value of the results following electrification, the absence of uniformity of equipment necessary for the interchanging of locomotives and rolling stock, and the undeveloped condition of the electric power industry.

The situation to-day is entirely different and the high cost of railway working has made it necessary to seek for every means of economy. If it is ultimately found that the electrification of suitable railway sections offers advantages over the present system of operating, taking into consideration the increased capital expenditure, electrification will no doubt be adopted.

The Electrification of Railways Advisory Committee have submitted their final report in regard to regulations, so that future electrification in this country may be carried out to the best advantage in regard to the interchange of electric locomotives and rolling stock, uniformity of equipment and/or other matters, and, while the Committee recommend certain conditions, they do not put any difficulties in the way of the adoption in future, with the approval of the Ministry of Transport, of any improvement in methods or appliances which may from time to time become available with increasing knowledge and experience.

The Railways Act of 1921 is another factor in the direction of uniformity, and while there may be differences in detail of equipment between groups, it is obvious that within groups there will be absolute uniformity in order to obtain the greatest economy and interchange of locomotives, rolling stock and other apparatus.

While the recommendations of the Advisory Committee may seem easy of fulfilment, it must be pointed out that many costly alterations will require to be made to the existing running line before electrification can become generally adopted, especially in regard to overhead equipment.

It will also be found that many bridges and tunnels have not the necessary clearance, and both rail-level and overhead equipment will have to be provided.

The problem now facing railway management is not merely based on the average number of passengers or tons per train-mile; it is more in the direction of finding a cheaper and quicker means of transportation over the existing lines, giving less congestion at terminals and yet providing for the future growth of traffic.

In general, railway receipts are proportional to ton-miles, and operating expenses to train-miles, and while every effort has been made to increase train loads it has not been possible to dispense with the frequent train service demanded by traders and passengers, and at a time like the present, when loads are at a minimum, practically the same number of trains has to be run as if loads were at a maximum—with the consequent difficulty of making the ton-miles receipts meet the train-miles expenses.

Motor vehicles, run over main public roads maintained at the taxpayer's expense (and the railway companies are perhaps the largest taxpayers in the country), are to-day competing with rail transportation for passenger and goods traffic, and, while it would seem that railway transportation should be cheaper, it is undoubtedly the delays inseparable to slow-moving, heavy traffic that have materially contributed to establishing the motor vehicle industry, which offers, as its one chief asset, quick delivery to the point where the goods are required.

If the present system of traffic working, especially short-haul traffic, does not efficiently serve the more congested districts through which the railways pass, something should be done to make certain that the traffic is not diverted to motor vehicles, as it is by no means certain that the revenue raised from long-distance traffic alone would pay for the upkeep of the railways.

It has to be admitted that the experience already gained in this country goes to show that, generally speaking, the existing electrified lines have justified their existence by paying their way and creating new traffic.

So far the principal field for electrification has been short-haul passenger service, and the greatest advantage is quicker acceleration and deceleration. In the case of short-haul suburban traffic, electrification has not only brought about an improved all-day business but has relieved the congestion at termini.

Multiple-unit trains have proved themselves to have enormous advantages over steam trains for this class of service, inasmuch as the system gives greater flexibility, and train loads can be varied according to the amount of traffic. The space of platform occupied is very much reduced, and short trains at frequent intervals can be run, as against long trains at less frequent intervals. Multiple-unit trains for suburban traffic also lead to many economies when compared with the corresponding steam trains, inasmuch as there is more mileage per day from guards and motormen, giving greater efficiency and less cost per train-mile. Power is used only when actually wanted, and there is an entire absence of smoke and cinders. In addition, there is less shunting and a consequent saving in staff, and, as reduced shunting means fewer movements of points and crossings, the life of these expensive items is lengthened and maintenance cheapened.

Station premises have been re-designed and put to a more valuable use, and the adjoining property has increased in value ; also, it is recognized that residential districts improve in popularity when given a service of electric trains.

During the past few years great progress has been made in the design of electric locomotives, and the substitution of electric for steam locomotives, notably on the North-Eastern Railway, is an indication that the advantages and economies are known and appreciated.

The fundamental difference between an electric locomotive and a steam locomotive lies in the fact that while the latter generates its own power the former only acts as a transformer of the power generated at a power station into haulage power on the track.

Sir Vincent Raven, K.B.E., the Chief Mechanical Engineer of the North-Eastern Railway, in a recent paper * gave the mechanical disadvantages of the steam locomotive as follows :—

" The locomotive being a complete independent unit, its power cannot be greater than the capacity of the boiler.

" To increase the boiler capacity obviously implies increased dimensions and weight, both of which offer great difficulties in regard to clearances and strengthening of bridge structures.

" On many British railways the limit of weight has been reached and further development of power is only possible at enormous expense.

" The boiler, cylinders, valve gear, crank-shafts and all reciprocating parts are costly to maintain. Turntables, fuelling plant and water-supply appliances must be provided.

" The cab is small and open to the weather, involving discomfort to the locomotive crew.

" The locomotive radiates heat and uses coal all the time steam is up, that is, during many hours when it is doing no work and either standing-by or coasting.

" The wear and tear of the locomotive on the track is considerably increased by the impossibility of accurately balancing the reciprocating parts."

Sir Vincent Raven said that the electric locomotive is not hampered by any of the above-mentioned objections and that it possesses other important qualifications, such as :—

The simplicity of mechanical construction and operation.
The increased power of acceleration.
A high scheduled speed, due to the possibility of heavy, short-period overloads, resulting in more frequent service and the increased use of existing tracks.
A uniform turning effort, resulting in a better factor of adhesion at starting and on gradients.
The absence of all reciprocating movement, and accurate balancing of all rotating parts.
Facilities for driving from both ends of a locomotive.
The accessibility of mechanical and electrical parts.
Better accommodation for locomotive crews, by reason of the increased available cab area and by the closing-in and heating of the cab.
The possibility of coupling two or more locomotives together under the control of a single driver.

It is evident that the working of a steam engine depends to a large extent on the skill of the crew in attending to the fire and the water-level, and in looking after a number of mechanical parts and generally " nursing " the engine so as to get the best out of it.

The process of preparing a steam engine for a day's work involves considerable time and labour, and after the day's work is finished there is another process of cleaning up and inspecting which also takes much time and labour.

The electric locomotive is always available for service, as it is only necessary to keep the motor clean, lubricated and provided with brushes in order that it may be always ready for immediate use by simply connecting it to the power line. The driver has only to step on board, close certain switches and move the controller handle, and when the day's work is over nothing has to be done except ordinary examination, oiling and cleaning for the next trip.

The electric locomotive can remain in continuous service if the traffic can be so arranged for at least 20 hours in every 24, that the lubrication and the small amount of cleaning necessary for the electrical equipment can be given by the crew at wayside stops during running and between trips. The driver will, of course, be fully occupied during running in watching signals and controlling the speed, but as the second man is not required directly in operating he will have plenty of opportunity to attend to the cleaning and inspection of all parts, where this can be done without interfering with the running and without risk to himself.

The shed work is reduced to the cleaning and inspection of brake blocks and the less accessible parts between the frame. These differences in preparation for service

---

* *Transactions of the North-East Coast Institution of Engineers and Shipbuilders*, 1921–22, vol. 38, p. 173.

and operation make it evident that the electric locomotive can remain longer in actual service and do more train-miles than the steam locomotive.

These are only a few of the advantages of electric locomotives over steam locomotives and, while they may seem to be all-important, it remains a fact that there are only very few of them working in this country.

The handicap of electric traction is that it must be instituted on a large scale. It is not possible to change one train only as in the case of a shipping company, which might put one vessel of a new type into commission at a time without interfering in any way with any other ship. To form a fair guide, any experiment has to be tried on a scale which involves heavy capital expenditure, which in these days is difficult to arrange for satisfactorily, while the risk of a comparative failure has to be carefully avoided. The term "failure" does not imply mechanical or electrical breakdown or even financial ruin, but it is obvious that if to the present capital an additional capital equal to the cost of electrification has to be added, the improvement in operation must be equal to furnish a return covering the whole.

The smallest experiment in the direction of electrification would involve a tremendous addition to the capital expenditure, with the consequent difficulties of earning the additional interest charges thereby involved.

It has been pointed out that all the first costs of electrification need not necessarily be charged to capital, e.g. the cost of electric locomotives or rolling stock can properly be charged to revenue under the ordinary process of renewals, as obsolete steam plant requires replacement and in many areas it would not be necessary to incur the cost of power stations, as under the Electricity (Supply) Act, 1919, energy can be purchased in bulk from the public supply companies at probably a lower cost than energy could be generated by the railway company.

Electricity would, of course, only be purchased in cases where the supply was adequate in quantity and regularity to meet the demand, and there is every reason to expect that the concentration of supply for railways and other purposes will bring about lower rates.

It has been said that the greater utilization of the available water power in Scotland would bring cheap energy to the assistance of the Scottish railways, but it has to be remembered that there is a limit to the length of the transmission line, i.e. a point at which the advantage of the hydro-electric power station is wiped out, and it is very doubtful whether hydro-electric power stations will ever be able to compete with turbo-generating stations in industrial areas.

It cannot be said that the Advisory Committee in standardizing a pressure of 1 500 volts d.c. added to the cost of electrification, and up to the present no other system has been put forward giving more economical results in working or showing less capital expenditure for equipment and rolling stock. The importance of having a standard system will undoubtedly lead to more definite progress and, as a result, cheaper equipment. As the result of standardization the manufacturing companies have made great preparations to cope with the railway demand. They are at the present time spending considerable sums on research work and so far they can claim to have carried out all the electrification of British railways.

During the past year many papers were read before this Institution descriptive of new or improved methods of dealing with the problem, and it is known to those interested in the subject that progress is being made along lines which will eventually reduce the cost of installation.

The practice of British railways has been to build and maintain, with considerable credit, their own steam locomotives and rolling stock, and whether this practice of building will be continued under electrification is a question for the future.

Shops for maintenance, repair and renewal will always be necessary, and the valuable experience gained in this direction would seem to indicate that there will be little if any change in the practice. It will, of course, be necessary to purchase electrical equipment for some time, but there is no reason why the mechanical part should not be built by the railway company, who know exactly what is required for their particular line.

Sir Vincent Raven, in his paper already referred to, deals with this aspect of the subject and he has built the mechanical parts of all the electric locomotives in use on the North-Eastern Railway, the electrical equipment being purchased from manufacturers of electrical plant.

Mr. Roger T. Smith, Chief Electrical Engineer of the Great Western Railway, read a paper before the Institute of Transport on May 8, 1922, in which he said that it seems worth while on the eve of a demand for electric locomotives for the railway companies to consider whether an organization and workshops design for efficient and successful maintenance is the best for constructing electric locomotives requiring electrical and mechanical research of the highest order, and the employment of every advance in electrical and engineering knowledge, not only in locomotive building but in several branches of electrical engineering. He went on to say that it also seems worth while to consider whether it would not pay the railways of this country at least to give a fair trial to the policy of helping to build up the manufacture of the electric locomotive by commercial firms who, with an important home market as well as a foreign market, would have an opportunity of creating a world trade.

Very little has been said in regard to the cost of electrical equipment for ordinary railway lines used for both goods and passenger traffic, and in his paper already referred to Mr. Roger T. Smith gives the cost per single mile of track at £4 000, i.e. £2 000 for line equipment and £2 000 for substations spaced 10 miles apart. This sum does not include anything for transmission, which might, in the case of some districts of Scotland, cost a great deal.

It cannot be said that all the pioneer work has been done; but what has been done has proved to be wonderfully successful. The element of uncertainty has been entirely eliminated and I am of opinion that electrification will go forward as rapidly as economic conditions justify the expenditure.

# SHEFFIELD SUB-CENTRE: CHAIRMAN'S ADDRESS

By H. West, Associate Member.

(*Address delivered at* Sheffield, *15th November*, 1922.)

I have decided to take for my address a subject with which I have been closely associated for the past 26 years, that is, "The Use of Electricity in the Iron and Steel and Allied Industries." In reviewing this subject it is not my intention to go very closely into details, but to confine myself to a general outline only, of what has been accomplished, followed by a brief statement regarding the important question of supply, and, finally, comments on some defects associated with present-day apparatus.

It is generally admitted that the iron and steel industries have for ages occupied a position of vast importance in the world, nor can the statement be gainsaid that the economical production of these metals is a matter of national importance. Iron and steel have played a greater part in the upbuilding of the material side of our civilization than any other metals. They represent an enormous investment of capital and are produced upon a scale not attained by any other industry, and it is undoubtedly true to state that the enormous progress which has been made in the development of the industry during recent years is in a great measure due to the economies effected by improved facilities for driving plant, handling materials, and conducting certain electro-thermal and electro-chemical processes which naturally followed the introduction of electricity.

The services rendered during the recent war established beyond doubt the great superiority of electricity as a means of transmission and utilization of power over all other methods; in fact it is now universally conceded that it stands first and that there is no good second.

Those who have visited a modern iron and steel works of large size will agree that there is no industry in which there exists a greater variety or number of difficult problems to be solved than in the application of electricity to the requirements of such works, and that this application has made gigantic strides during the short period which has elapsed since its introduction.

It is probably true to say that more electrical power per head of working force is used in the steel industry than in any other industry; in fact it has become so much a part of the everyday life of the plant that few realize how dependent we are upon it. From the office to the despatch bay in the works it plays an important part, whether it be used for addressing envelopes, ringing bells, or driving the heaviest machinery; in fact, directly or indirectly, every operation is dependent upon its aid.

Some idea may be formed as to the magnitude of the equipment required to meet the needs of a concern engaged in the production of iron and steel and the associated businesses of shipbuilding and railway rolling-stock manufacture, when it is considered that for this purpose a total of something like 2 800 motors are required, having an aggregate brake horse-power of about 90 000, and ranging in size from a fraction of 1 h.p. to a little under 20 000 h.p., with generating and/or substation plant sufficient in capacity to meet the demands created by these motors, together with that due to other uses of electricity.

During the later years of the war a number of the best-known concerns in this district were collectively using something like 220 000 000 units of electricity per annum. The requirements of this same group were met immediately before the war by something under 80 000 000 units in the same period. Nevertheless, a little over 30 years ago an electric motor was a rarity in a steel plant in this country, although some progress had been made abroad in this direction. Prior to that time, electrical engineers at home had devoted so much attention to the then important questions of central electric light and traction stations that they had little time to consider the industrial use of electricity which was destined to play such an important part in the years which followed. True, a few far-sighted men were using this drive for certain specific purposes, but these applications formed conspicuous exceptions. In general, those connected with the industry were sceptical regarding the suitability of an electric motor to meet the exacting demands of steel-works practice. The drives then in use were at least satisfactory and represented what engineers had found to be the best after many years of experience. If the plant was making money, what need to change? If not, the cost of installing motors was prohibitive.

Some of these early applications related to machines which required to be diffused rather than concentrated, e.g. punching, shearing, and bending and straightening machines, cold saws, etc. It had been the general practice to place a separate non-condensing engine to operate each of such machines and distribute the power thereto by an extensive system of steam pipes from centrally placed boilers, or from a multiplication of boilers distributed in small groups, each group requiring separate labour for firing and for coal- and ash-handling. Not only was the production and delivery of the steam to the various points wasteful, but there was also a tremendous loss in its use, as a consequence of the continuous running of most of the engines, although they were doing useful work for only a small portion of the time.

The advent of electricity rendered possible a great advance, as a more economical type of engine centrally placed could be employed to drive a dynamo, with cables instead of steam pipes, and motors directly applied to the machines.

Following the class of machinery already mentioned, steps were taken to drive machine tools, live rollers, screw-down and skid gears, and cranes of various types. In every instance the displacement of uneconomical engines and long lengths of steam pipes or shafting led to further economies in the cost of labour, fuel and upkeep, and a much more flexible and efficient form of drive was secured, with the advantage that the driven machines could be more conveniently placed in relation to each other and the work in hand.

In the face of many failures of these early machines, the motor attained a responsible position, and the new system became so unanimously recognized as being sound that the progress of conversion of existing plants and the application of motors to new drives where possible went forward with great speed, until to-day the electric drive is the only one considered for all purposes to which it can be applied.

With the ever-widening duties of the motor came attempts to apply it to the heavy main drives of the rolling mills themselves, and in entering this field, so long held exclusively by the steam engine, it met with the greatest opposition on reversing mills, the major causes of which were probably prejudice and initial cost. The progress made in this direction, however, can also be recorded as remarkable. During late years it is represented by a very steeply rising curve, and there now remains very little argument in favour of the steam engine for such drives. In connection with this curve, it may be of interest to mention that the first electrically-driven mill was set to work in Sweden about the year 1890, and the first large equipment in this country was installed in 1904.

To-day, according to a recent table,* there are now over 600 electrically-driven mills in operation, the driving equipment for which was supplied by British manufacturers, and the great bulk of which are installed in steel works in this country. The list constitutes a marvellous record of development, and comprises mills capable of turning out all classes and forms of rolled materials, inclusive of tubes, tyres, sheets, rails, girders, etc. Considerable impetus to the advancement of this class of drive was created by the development of adequate and reliable gearing. This rendered the low-speed motor, to a large extent, unnecessary, thereby reducing the cost of many installations.

There are naturally a number of varieties and types of these applications, depending upon the drive in question. If the drive is a continuous one, i.e. if the mill is so arranged that the motor runs continuously in one direction at a constant speed, the application is comparatively simple, as the wound rotor, three-phase induction motor serves the purpose admirably.

If the drive in question is one demanding reversal, with or without speed regulation in either direction, the application of the motor becomes more complicated, due mainly to the size of machine required, coupled with the rapid reversals necessary. In this case one has recourse to the Ilgner system which has previously met with great success in its application to large mine hoists.

Other methods have been developed for meeting special requirements, but I do not propose to dwell further upon this subject.

There still remain a very large number of engine-driven mills, and it would seem that the greatest field for additional motor-drives in the next few years lies in replacing many of these engines, as doubtless such a step would lead in many cases to economy and increased output.

One of the fundamental considerations controlling the rapidity of production of steel is the handling of materials at all stages during the process of manufacture, and in this connection overhead and other numerous special types of cranes have contributed in a very large degree to the present-day highly developed state of the plant, but again such progress was only rendered possible by the adaptability and ease of control of the electric motor for this purpose. Adherence to the earlier methods employed for the transmission of power to cranes would have rendered unattainable the varied movements and operation which are to-day possible.

One great extension in the use of cranes is due to the increasing employment of electromagnets for rapidly and cheaply handling materials at various stages between the stock yards and the shipping department. Very great economies in this item of labour alone have been effected by such means.

Apart from applications involving power supply for mechanical operations, electricity has, of course, been employed for a great number of years as the principal lighting agent, and it has found new fields for itself in connection with the reduction of ore, the melting and refining of steel, the electro-deposition of pure iron, and the electrostatic precipitation of suspended particles in blast-furnace gases intended for use in gas engines. It has also been successfully employed as a means of producing high temperatures for re-heating purposes, and again, through the medium of the pyrometer, for indicating and recording temperatures in connection with all parts of the plant.

As a means of jointing metals, in repairing cracks or breaks, salvaging defective castings, and for metal-cutting purposes, all included under the general heading of "Electric Welding," electricity has proved of great service. Prior to the war, little had been done in this respect, but great strides were made when the confidence of the engineering world was established due to the successful welding carried out on the damaged parts of the interned German ships at New York in the spring of 1917.

In a lesser degree it has been of service to the metallurgical chemist, who has applied the electrolytic method to the separation and determination of several of the metallic constituents of steel. Up to the present—setting aside the question of lighting—the production of electric steel is the most important of these special applications.

The use of the electric furnace was somewhat limited before 1914. It was, however, making headway, although then regarded as being in its experimental stage. After the outbreak of war, the demand for a greatly increased output of special alloy steels, coupled with the necessity for providing a means of dealing with the enormous accumulations of turnings produced in the manufacture of munitions of war, resulted in the number of furnaces being rapidly increased, until at the cessation of hostilities there were upwards of 140 in service or in course of erection. About 120 of these were for purposes of steel manufacture and had a total charging and kVA capacity of 384 tons and 98 769 kVA, respectively, and a total nominal output of about 31 000 tons per month, based upon five days per week and four weeks per month. These figures are quoted from a paper by Mr. R. G. Mercer,* to which I would refer members for very valuable information on this subject.

---

* *Electrician*, 1921, vol. 87, p. 647.

Unfortunately, I cannot enlarge here upon the processes of electro-deposition of pure iron or electro-smelting of iron ore. I shall, therefore, confine myself to the statement that both processes have been successfully employed on a commercial scale and offer great possibilities for the future, given an abundant and cheap supply of power.

A question which has recently caused a great deal of controversy in steel works circles is that relating to the respective merits of alternating-current and direct-current plant for the purposes of any particular service. Each system possesses peculiar merits of its own, and as the iron and steel works of to-day either generate or receive at least a portion of their energy from public supply mains on a high-tension multiphase system, there is an increasing tendency to utilize, wherever possible, a.c. apparatus in place of the d.c. type which so long held the field, owing to the saving which can be effected in copper, transformers and converting plant.

With regard to motors, the principal factor deciding the type is that of speed control, but it may be generally stated that machines of either class will give equal satisfaction on certain drives if at the time of selection all phases of the problem receive full and proper consideration. This statement is based upon my experience in connection with an a.c. plant laid down 16 years ago for all purposes in one of the works over which I have control. The drives included cranes and mill auxiliaries, comprising "screwdowns," skids and live rollers, and, though much trouble was experienced due to certain motor defects to which I shall refer later, I am confident that the duties were as satisfactorily performed by this class of machine as would have been the case had any of the available d.c. machines been used in their place.

No matter in what branch of electrical work a man may be engaged, he is always interested in electric power generation. From the foregoing general outline of what one may term the consuming devices in his charge, it will be readily conceded that the problem of supply, whether it be derived from outside sources, or generated within the works, is of profound importance and interest to the steel works electrical engineer.

The question of supply is to-day a much more vital one than when lighting constituted the main bulk of the load, and the three main considerations, all of equal importance, are continuity of service, safety of plant and workers, and low cost per unit.

Considering the capital involved and the nature of the work in hand, an interruption of the supply, even for a few moments, is a very serious matter, and every precaution should be taken to avoid it, as not only does it lead to loss of output, but the lives of many of the employees are placed in jeopardy, partly due to the extinguishing of the lights, should the failure occur during the night, but mainly due to their position in relation to molten or hot metal. In many cases great monetary loss is occasioned by the cessation of supply during casting operations, rolling, forging or otherwise dealing with molten or hot metal. Damage also frequently occurs to electrical and other machinery due to the inability to remove it from hot places or out of contact with heated materials. Danger also arises due to the impossibility of operating pumps for the purpose of the works water supply or the important duty of boiler feeding.

For many years all the electric power was produced within the works by privately owned plants which, from very small beginnings, had been extended from time to time to keep in step with the ever-increasing demands made upon them, until, in many cases, such plants were of relatively large capacity compared with the then existing central generating stations. There was then no question as to the advisability of generating their own power, as this was the only way in which it could be obtained.

These earlier installations were, in the main, of the d.c. type, the supply pressure being usually 220 volts, determined by the initial class of motor available, and partly also by considerations of safety. The handicap of this low voltage was keenly felt, as the load and areas to be covered increased, due to the continued extensions of the plant. This difficulty was overcome in some instances by the simple plan of modifying the arrangement to that of the three-wire system, balancing all existing motors and lights on either side of the neutral and connecting any additional motors across the outers. In other instances, plant laid down for extension was of the a.c. type, giving a supply at medium or high pressure which could be applied direct to many motors without the intervention of either transforming or converting apparatus.

Since many of these stations had been kept up to date by replacing obsolete equipment as more efficient and larger units became available, and especially in those cases where waste heat was utilized for generating purposes, the cost of electricity was exceedingly low. Moreover, as the questions of simplicity and reliability were constantly uppermost in the minds of those responsible for the lay-out and operation, it naturally followed that the three important requirements already quoted were usually met in a most satisfactory manner.

The feeling of security associated with this state of affairs was, for a time, a deterrent to the adoption of a supply for part or the whole of the requirements, derived from a company-owned or municipally-owned station. Later, however, this class of service was accepted in many instances in preference to extending or renewing the private plant, especially where waste heat was not available in sufficient quantity, or in congested areas when the question of space, or of water for condensing purposes, presented difficulties.

---

* *Journal I.E.E.*, 1919, supplement to vol. 57, p. 254.

It is seldom that a failure of supply can be attributed to a total shut-down of station plant. More often than not it is due simply to the opening of a feeder switch. When this occurs in the case of the privately owned plant situated within the works, it is a matter of only a few moments to restore the supply. In the worst case, assuming that the whole of the generating units are disconnected from the busbars, the engines will continue to run with the machines excited, thus enabling one of their number to be immediately put into service to supply those departments where risks of loss of molten or hot metal are existent.

The matter is not so simple in the case of a large consumer dependent upon an outside supply, as due to the nature and pressure of the supply considerable extra apparatus is required to deal with it before it can be passed on to the works, and, unlike the illustration given for a private station, much additional, valuable time is lost for the purpose of starting and synchronizing converting machinery and operating the extra switchgear involved.

Interruptions of longer duration due to causes of a more complex nature almost invariably lead to a greater loss in the case of an outside supply than with private plant, as in such instances one is usually ignorant as to when work may be resumed. This leads to great uncertainty concerning the best course to adopt in order to reduce the consequential loss and danger to a minimum.

Although the cost of electricity does not represent a very large proportion of the total cost of each ton of metal produced, with the exception, perhaps, of that used for melting purposes, it is nevertheless of the utmost importance, considering the enormous amount of the annual bill, that every endeavour should be made to reduce it well below the prices ruling at present. In view of this, and also the necessity for conserving the nation's fuel supplies, it would seem to be incumbent upon those concerned with the reorganization of the electricity supply of the country seriously to consider close co-operation with steel and other works with a view to the utilization of all available waste heat, as undoubtedly this would lighten the burden arising out of the high cost of fuel and its conveyance to the point of use.

Any further segregation of the power plant from the steel works will depend largely upon the success of efforts in this direction, and also upon the requirement that uninterrupted service throughout the year can be guaranteed by the provision of adequate devices for the purpose of isolating faulty apparatus, or sections, without interference with the sound ones.

Another serious handicap to the immediate displacement of all private plant and, to some extent, the continued safe operation of apparatus already connected for the control of outside supply, arises out of the present-day trend towards increased capacity and the connecting together of public generating stations. This centralization of large amounts of energy introduces serious possibilities of considerable destruction should a short-circuit occur on a consumer's premises, and places very great responsibility upon the reliable operation of high-voltage apparatus, in particular upon extra-high-tension switchgear. The capital expenditure required to guard against such possibilities will be greater than that entailed when connecting up to a less pretentious scheme, thus tending to discount any advantage to be gained by the utilization of large and more efficient units. This fact alone renders necessary a reduction in the unit charge for extra-high-tension energy to enable the outside supply to compete favourably with the private plant from the point of view of cost per unit at the low-tension works switchboard.

I have already stated that steel-works present a number of difficult problems in the application of electrical apparatus. These difficulties do not disappear with the installation and setting to work of the machines, etc., but rather give way to a number of others arising out of the unsuitability for this special purpose of much of the available equipment.

Generally speaking, the steel-works plant itself is massive, rough, and subject to severe shocks and stresses. Its limits of adjustment are wide, and it is in the care of men who are accustomed to materials, tools and methods which are the reverse of delicate. It is, therefore, necessary that the electrical equipment should be selected with care, the purpose in mind being reliability, simplicity, the human element, interchangeability and easy renewal and repair. Above all, it should be rugged in build and not liable to deterioration due to the ever-present corrosive gases and dirt-laden, hot, and often humid atmosphere.

Since the processes are continuous ones, and the stoppage of one machine frequently holds up a whole section of the plant, it is just as important to guard against breakdown as it is to ensure continuity of supply to the machines. The first equipments included apparatus of the then standard designs, but it was soon evident that something entirely different was required for this special service. The early motor at least, with all its faults, was a more reliable article than the starter of those days, and much excitement was at times occasioned when starting up some of the motors, due to the nature of the only available starters, which consisted of coils of iron wire arranged to be cut out in steps by means of a multiple-contact switch, but without any device to protect the contacts from the destructive sparking which occurred. A separate switch—not interlocked with the starting handle as is usual to-day—was provided in the shunt field circuit. The latter was, of course, intended to be closed before, and opened after, manipulating the starter handle. On occasions this sequence was followed, and when the unsupported resistance coils or the arm and contacts of the starter did not form too close attachment for each other the motor in due course acquired full normal speed. There were times, however, when the operation was incorrectly performed, and both the operator and the motor exceeded the speed limit, often with disastrous results to the latter.

As most of you are familiar with the great improvements which are embodied in the starting and controlling apparatus available to-day, numerous types of which have been developed to overcome the difficulties which bitter experience has pointed out, and to meet the demands of modern practice—assisted in great measure by the requirements of the Home Office Regulations—it is not my intention to refer to the various stages through which progress in this connection has carried us, but I should like to point out that, notwithstanding the many excellent examples, there still remains room for considerable improvement with a view to the reduction of the cost of upkeep and the removal of the uncertainty in regard to correct operation. For instance, resistances in many cases are deplorable. They are neither durable nor dependable, due to their liability to corrosion and breakage. The method of assembling, clamping and ventilation often leads to endless trouble. Then, again, the switch parts and contact surfaces are frequently incorrectly proportioned, thus causing heating. Interlocks, forming a very vital part of many modern equipments, are much too flimsy in character.

Much of the switchgear of other classes required for use in steel works also leads one to hope for improvements. Overcrowding of details, and unnecessarily light construction, often lead to trouble, while many otherwise excellent designs are frequently marred by the inclusion of terminals or trifurcating boxes totally unsuited to the size of cable required for the job in hand. Back or internal connections are also a constant cause of failure, in consequence of the slipshod manner in which they are arranged.

Unfortunately, the trials of the engineer do not end with switchgear. Motors also cause him much anxiety, due to their deficiency in mechanical strength. The frequency of reversal, and the heavy jars to which the motors are subjected, often lead to fractured end-brackets or to the armature or rotor core rotating round the shaft. The use of insulating materials unable to withstand the rough usage or action of corrosive gases leads to frequent failure, and many instances exist of otherwise good machines being spoiled by the inclusion of shoddy terminals or brush-holders.

Again, we have all at some time or other suffered inconvenience and expense because of the difference in speed, rating and dimensions of the various makes of machines. It is not always possible to carry sufficient spares of each type to meet all demands, and, although the differences mentioned are often apparently small, there are, nevertheless, definite limitations to the substitution of one make of motor for another. In the early days, and even at the present time, the manufacturers have standardized this lack of interchangeability. An initial order for motors seemed to be considered a virtual guarantee of subsequent orders, due to the well-recognized reluctance to carry a greater range of spares than necessary ; yet the modifications introduced by the makers themselves in the normal improvement of design have rendered many of the earlier features obsolete, and have thus, in effect, increased the number and range of spares required even where a given make of motor may have been retained throughout the works.

The steel industry, constituting, as it does, one of the most remunerative fields for the activities of the electrical equipment manufacturer, it would seem to be well worth while to spare no efforts to develop a line of apparatus and machines in every respect adapted to meet the exacting requirements outlined. Something has been done in this direction so far as the " live roll " motor is concerned, but surely it should be possible, through the medium of their organization, definitely to fix the principal mechanical dimensions of these and other machines, such as the length and diameter of shaft, the size of bearings, the distance from the centre line of the shaft to the underside of the base, the spacing and size of foundation bolts, as well as horse-power rating, speed, and type of brush.

With limitations only of these characteristics, each manufacturer would still be at liberty to improve, if possible, details of both mechanical and electrical design, and thus maintain wholesome competition and progress.

Before bringing my remarks to a close, I should like to thank the authors of several previous addresses and articles which have appeared in the technical Press upon which I have drawn, to some extent, for the purpose of finding, in some instances, a better way of expressing what I so strongly think and feel.

In conclusion, I would remind you that the iron and steel industry is passing through the most trying time that has ever been known or heard of, and that when we do again get the whole of the wheels turning it will be incumbent upon each one of us concerned to exercise the utmost economy in the arrangement and running of our plant, so that by its greater efficiency it may assist in no small degree in meeting the competition which is certain to be encountered.

With due regard for established precedent, we should be ever alert to grasp the significance of new ideas and, with the courage of our convictions, to adopt them, but

> Be not the first to cast the old aside,
> Nor yet the last by whom the new is tried.

Such advice is indeed conservative, and by following it we can make the electrical departments of our steel works of enormous service and value, not only to the great industry itself, but also to the nation in general.

# TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By W. P. Richmond, Associate Member.

(Abstract *of address delivered at* Middlesbrough, 16*th November*, 1922.)

At the beginning of the last session the trade of this district was in a very bad state, and we hoped that by now conditions would have become more normal, but there is no doubt that Cleveland is passing through the darkest days in its history, with perhaps the one exception of the crisis in 1879. The present crisis differs from all its predecessors, however, in that it is universal. Our trade conditions, bad indeed as they are, prevail throughout the United Kingdom and extend to every corner of the globe.

To understand properly the present crisis, we must first of all investigate the general causes underlying the world-wide depression, applying the results of that examination to our own patricular case, and then take into consideration any local or immediate difficulty.

We shall see that the causes are of two orders : (1) General and international ; (2) National and local. Although these two are inextricably related, I propose, for purposes of clarity, to deal with the two separately.

## General and International Causes of Trade Depression.

For any industrial country to be prosperous it must have foreign trade, and the non-existence to-day of international trade is the cause of the present world-stagnation. The causes of the non-existence of international trade are threefold :

(*a*) Reparations, and allied and other debts.
(*b*) Fluctuations in foreign exchanges.
(*c*) Bad policy in the new commercial treaties and regulations.

(*a*) *Reparations, and allied and other debts.*—Following well-known economic laws, the payment of war debts naturally forces up taxation on the one hand, and on the other produces an adverse effect on national credit abroad. The allied nations must be in unison, and it is obvious that the only remedy is one which will set Central Europe upon her legs again, first so as to be able to pay any reasonable demand made upon her, and secondly so that she can again become a fruitful market for our produce. With this should be coupled some desirable method for the liquidation of war debts.

(*b*) *Instability of foreign exchanges.*—Immediately after the war the German exchange began to fluctuate enormously, largely, as we have seen, as the direct result of war debts.

At the same time, the exchanges in other countries began to fall, for similar reasons, only perhaps not to such a colossal extent, and gradually all foreign markets became closed both to ourselves and to America, because our prices were prohibitive, and eventually the exchange question developed to such a degree that foreign iron and steel could be sold in the Tees-side district at shillings below our cost of production and still give a good profit to the foreign manufacturer.

This state of affairs must be remedied before international trade can be re-established to its pre-war degree, with certainty, profit and mutual advantage. The remedy lies in reverting to a gold standard in all countries, as well as in keeping annual national expenditure within the limits of annual national revenue, this latter, of course, applying particularly to Central Europe. This means, above all, considerable reduction in the amount spent on armaments. At the International Financial Conference at Brussels in 1920 it was shown that on an average over 20 per cent of national revenues were spent on armaments ; also that, as far as Great Britain is concerned, 60 per cent, or 12s. in the pound, of the taxes is spent on wars, either old or new.

(*c*) *Bad commercial policy.*—Several countries have introduced since the Armistice various trade regulations whereby the importation of certain articles is prohibited. The object of these regulations seems to be to make exports exceed imports. Now, it is wrong to imagine that because a country exports more than it imports it must be flourishing, since the exact opposite might easily be the case. Actually the ratio of exports to imports has no direct bearing upon the flourishing condition or otherwise of a country. This scheme must not, however, be confused with legitimate tariff reform, which has as its object the raising of national revenue. The obvious remedy in this case is the abolition of such regulations, with a view to fostering—not hindering—trade. Time, however, will do much to teach misguided countries that such methods are wrong, and will only defeat their own objects.

Such, then, are the general causes of the present world-wide depression, and it would be well now to investigate the immediate causes in the light of the foregoing, remembering always that Cleveland and its trade form but the part of a whole.

## National and Local Causes of Trade Depression.

Iron, steel and shipbuilding are our local staple industries, and on the cessation of hostilities in 1918 the whole world was crying out for iron and steel. Various industries had been starved during the long years of war. Railroads badly needed repairing ; in some cases even replacing, and rolling stock, etc., was depleted. Yet, as we have seen, the boom was but short-lived. Whilst the demand was good, the supply fell far short of expectations. There was a shortage of coal supplies, and also of ironstone. To this difficulty was added another, namely, the truck shortage, causing delays in securing supplies and despatch of finished products. Then came the moulders' strike, the engineers' strike, the coal strike and the railway strike. The combined effect of these was to cause many furnaces to damp down, whilst others on reduced blast were only able to produce poor quality pig instead of good marketable brands. Much valuable coke was thus uselessly consumed. Then, because our supply in no way met the demand, iron-masters refused to allow the export of pig iron until the home markets were satisfied. The removal of the embargo was subsequently brought about, but unfortunately not until foreign markets were closed to us.

Such was the position in 1919, but by the end of 1920 the reverse was the case, for what little demand existed was met by cheap foreign iron and steel.

### THE FUTURE OF THE CLEVELAND INDUSTRIES.

On the eve of war the world consumed 80 million tons of pig-iron and steel ingots per annum. As a consequence of eight years' abnormal conditions there is a world shortage of iron and steel of at least 300 million tons, the major portion of which will have to be replaced within a reasonable period. This is, of course, speaking in the abstract, but there are signs of immediate requirements. Nine countries out of ten are needing vast railway replacements and extensions. Projected schemes in Brazil alone will consume 16 million tons of steel. South Africa has just passed a new Railway Construction Act and has sent out inquiries for material. India requires additional railways of a mileage greater than that for the whole of Great Britain. Bulgaria, Latvia, Belgium and Spain will soon be in the market for railway material.

We have also at the moment 3 million tons of steel ships over the age limit waiting to be broken up and replaced as soon as the price of steel falls sufficiently to enable new ones to be built. Each 2·1 tons of shipping requires 1 ton of steel ; thus more than an additional $1\frac{1}{2}$ million tons of steel are required for ships alone.

For some years our pig-iron exports have been falling, but our steel exports are rising, which in itself is a good thing, for it means that more work will be done in the country and in this district. Unfortunately, however, the pig-iron production is not up to the steel requirements in quantity. Steel is fast becoming our staple industry, and we must realize the fact and work accordingly. During the war the productive capacity of our country had been permanently increased. Many new works were laid down ; many reconstructed or remodelled and extended, and there is now an ample sufficiency of plant. This also applies to Cleveland and we ought therefore to be in a position to supply steel to a degree hitherto unknown. Moreover, railway rates, while falling, are hardly ever likely to reach the pre-war rate. So, instead of shipping hematite pig to Sheffield to be converted into forgings or boiler plate—as was formerly done—often to be returned to the seaboard for shipbuilding or for export, the tendency will be to lay down additional steel plant in Cleveland. The future of Cleveland therefore appears to be very hopeful.

### ELECTRICAL PROGRESS.

Turning our attention now to the electrical side of the question, I think we can congratulate ourselves that the North-East Coast is one of the most progressive parts of the country. Our power company is the largest in Great Britain, and ranks as one of the largest in Europe. We have a railway company which has adopted entirely new methods, and has attained extremely good results. We have mines wholely electrically operated, and iron and steel-works almost entirely so. It is the application of electricity to iron and steel-works which mostly concerns us in this district.

One of the first mills to be driven by a motor in this country was a small one at the Queensferry works of Messrs. Willans and Robinson. This was used for cogging-down ingots into blooms from which the tubes for their water-tube boilers were made. The motor was of 285 h.p., direct current and compound wound. When the load came on, the motor slowed down by reason of the compounding and allowed the flywheel to take effect. The power was transmitted to the mill by means of a rope drive. This plant was installed in about 1904.

During the next few years many small drives with no particular points of interest were put in for tin-plate mills and the like. In 1905, however, a very much bolder scheme was adopted at the Birkenhead works of the McKenna Process Company, their works being entirely electrically driven. There were several points of interest in this plant. It was the first time that rolls had been directly driven electrically ; the prime movers were the first turbines made by a firm other than Messrs. Parsons, and it was the first large three-phase installation manufactured in England. This plant may be taken as the first serious attempt to electrify rolling mills. A few years later two small reversing mills were installed in this district, followed almost immediately by several "three-high" variable-speed mills. In 1906–7 the first Ilgner sets were put in for the Clyde Navigation Trustees at their new "Rothesay" dock at Clyde Bank, to operate coal hoists and cranes.

These large flywheel sets paved the way for large reversing rolling mills, and in 1911 a large 12 000 h.p. reversing mill was installed in this district, and electrical power had been applied to rolling mills of all sizes.

There is little doubt that the duty of live-roll motors is the most severe that any motor is ever called upon to perform. Particularly so is the case of that immediately before the saw. Motors in such positions are constantly being started, stopped and reversed, so that the power used in starting and reversing is much in excess of that absorbed in doing useful work. For the same reason they have to be put in of much larger size than the actual horse-power required, on account of the excessive heating. What is required is a reversible clutch, and a constantly running motor. Recently there have been several, sometimes termed hydraulic clutches, put on the market. These are not only a clutch but are made with a gear ratio between the primary and secondary motion. If these devices will withstand rolling mill work, and I believe they will, they will be of great advantage for rolling-mill auxiliary drives. Not only will they supersede controllers or contactors, which require much attention, but they will allow of the use of the ordinary industrial type of motor, as there will be no excessive heating caused by reversing. Still further advantage will be gained and lower first cost attained if the ratio of the clutch can be made so as to eliminate entirely any further reduction gear. Such first costs would be much less than at present, when, besides the special motor now employed, the controller or contactor and the gears—two are usually employed—could be dispensed with.

### THE POWER HOUSE.

For several reasons it is somewhat difficult to compare generating costs in works with those of public supplies. The wages in works' power houses usually fluctuate, the men being paid according to the price of iron and steel. The plant has grown with the works, and the plant units are possibly not of a size best calculated to keep down costs. The load factor is in favour of the works, which, of course, generate more cheaply than they can buy. On the whole, however, I think that the cost of generation might be still further reduced.

Both in the lowness of running costs and in the small amount of adjustment and attention required, the steam turbine is far in advance of the gas engine.

### ELECTRIC LOCOMOTIVES.

In a few years' time, when the electric locomotive has taken the place of the steam locomotive, we shall look back on the boiler, firebox, cylinder, side rods, etc., of the steam locomotive as a bad dream, for the electric locomotive is bound to come.

The disadvantages of a steam locomotive are that the boiler, cylinder, valve gear, crankshafts and all reciprocating parts are costly to maintain. The cab is small and open to the weather, thus involving discomfort to the locomotive crew. The engine radiates heat and uses coal while steam is up, i.e. during many hours when it is doing no work. The wear and tear of the locomotive on the track is considerably increased by the impossibility of accurately balancing the reciprocating parts.

The electric locomotive is not subject to any of the above-mentioned objections, and, in addition, it possesses many other important advantages.

The North-Eastern Railway have had eight years' experience with the locomotives on the Newport–Shildon line, and Sir Vincent Raven in his paper read before the North-East Coast Institute of Engineers and Shipbuilders in December, 1921, gives the figures for repairs of two steam and one electric locomotive as follows :—

The first steam locomotive after running 51 000 miles cost 5d. per mile.

The second steam locomotive after running 56 000 miles cost 5·572d. per mile.

The electric locomotive after running 100 010 miles cost 1·316d. per mile.

In other words, the cost of repairs for the electric locomotive was only one-quarter of that for the steam locomotive. In the United States the cost of repairs is rather more in favour of the electric locomotive, being only about one-fifth of that for the steam locomotive.

It is not, however, the main-line locomotive which is of the greatest interest to us, but rather the shunting locomotive suitable for use in iron and steel-works. Such locomotives are of two types, the straight electric locomotive, i.e. that getting its supply of electricity from an outside source, and the battery locomotive, and sometimes a combination of both types.

Sir Vincent Raven in his paper read before the Institution of Mechanical Engineers in August of this year instances two straight locomotives which for 17 years have been working on the Quayside line at Newcastle for shunting purposes. They have been in the shops only three times for thorough overhaul, and their daily service occupies about 18 hours. For the whole of the year 1921 the average cost per engine for repairs, inspection, preparing, cleaning, etc., was £103. This figure is rather high, as it includes in one of the locomotives some special repairs which would not be required in an ordinary year. The corresponding figure for steam locomotives doing the same class of work for the year 1921 would be about £610.

The straight electric locomotive is undoubtedly a better engine than the battery locomotive, owing to the fact that the latter must necessarily impose certain restrictions which do not exist in the straight electric locomotive. In making this statement I am not in any way detracting from the usefulness of the battery locomotive, as experience has proved beyond doubt that the battery locomotive is an almost ideal class of engine for industrial shunting-yard duty, and in the majority of cases it is admissible where the trolley electric locomotive could not be considered.

It is impossible to use the straight electric locomotive in the works proper, on account of the necessary overhead line or third rail, but it is advantageous in some cases, e.g. where slag-tips or raw-material stores are at some distance from the works, to use a combination, the battery being the source of supply in the works and an overhead line in the outlying parts.

Probably the first question to be asked is : Will an electric locomotive do all that a steam locomotive will do ? The reply is, of course, in the affirmative. An electric locomotive requires only 80 per cent of the adhesive weight needed by a steam locomotive.

When dealing with the battery locomotive there is a certain limitation due to the heavy rate of discharge which is demanded of the battery when hauling a load up the maximum gradient, but, generally speaking, there is little doubt that most batteries, if carefully designed, are capable of dealing with any ordinary shunting-yard gradient. One may take, say, 3½ to 4 per cent as representing a very severe gradient, and I consider that good results would be obtained on such a gradient if the battery capacity is suitably selected. There are quite a number of battery locomotives running in this country and doing quite satisfactorily all that is required of them, and in the United States at present there are 2 400 in operation.

*First cost.*—The question of first cost is a very important one and is governed largely by local conditions. If one takes the worst conditions, where only one steam locomotive is used, and consequently one battery locomotive is to take its place, then the first cost may be a serious handicap, as the capital value will possibly be in the nature of 1·8 for electric battery traction to 1·0 for steam traction, but there are few yards, however small, where one could afford to risk allotting the shunting duty to one steam shunter. However, when one comes to consider the substitution of a batch of steam locomotives by electric locomotives, the capital costs are much more in favour of the latter. From my experience I should say that 8 battery locomotives would carry out the same duties as a fleet of 10 steam shunters.

On the Newport–Shildon line 10 electric locomotives replaced 27 steam locomotives, the former, of course, being a more powerful engine than the latter. In iron and steel-works we are not in such a happy position, as we are not able to make our engines heavier and so reduce the number.

Recently a scheme was investigated for replacing 14 large steam locomotives, each weighing 34 tons, by electric locomotives. It was decided that it would be advisable to purchase 12 electric locomotives at a cost of £115 000. The operating charges of the existing steam locomotives were examined very thoroughly, and only proved results were taken as the operating costs for the electric locomotives, and it was found that an annual saving of not less than £21 000 would result.

*Saving of fuel.*—Although the saving of fuel due to the use of electric locomotives in place of steam on main lines is very great, it is not nearly so great as that shown in a shunting yard. The saving is again increased in iron and steel-works on account of the locomotives having to stand inactive, waiting for furnaces to tap, and the like, for long periods.

From a great many tests taken on many sizes and types of steam locomotives, it has been found that for every 13 lb. of coal consumed on a steam locomotive 1 kWh is required from the battery of an electric locomotive. Now, allowing for a battery efficiency of 70 per cent, then 1 kWh of battery input is necessary for every 9·1 lb. of coal consumed in the steam locomotive. In a modern power station 1 kWh can be generated by 2 lb. of coal or its equivalent of other fuels, which shows a fuel saving of 4½ to 1 in favour of the electric locomotive. At present-day prices coal such as is used in a power station costs 17s. 6d. per ton, whilst that suitable for a steam locomotive costs 26s. 6d. per ton, showing a 7 to 1 saving in the cost of fuel in favour of electric battery locomotives.

In some cases it may be impracticable to charge the batteries direct from the generating plant, and some means of conversion, such as a motor-generator, may be necessary. The saving of fuel in such cases will not be so great, as the efficiency of the converting plant will have to be accounted for. So as not to favour unduly the electric locomotive, let us say that the efficiency of conversion, and the loss in the mains is 80 per cent. This would leave us with savings in the amount and cost of fuel of 3·6 to 1 and 5·6 to 1, respectively, in favour of the electric locomotive.

*Batteries.*—I consider that one would be quite safe in taking the life of lead cells to be about 3 years, and of nickel-iron batteries at least 7 years. While the cost of the nickel-iron battery is very much greater than that of lead batteries, I find that the nickel-iron is the more economical when capitalized over 6 or 7 years. In addition, the nickel-iron battery has several other advantages.

Another very important point is the charging of the battery, and its ability to run a shift without charging. It is not, however, necessary to let the battery run down until it requires to be completely re-charged, but it can be partially charged at such time as the locomotive is idle. It is quite practicable to install a battery to give, with the types of cell now manufactured, an effecive output of 170 kWh on a 2-axle locomotive. It follows, therefore, that a 2-axle electric locomotive will do the work performed by a steam locomotive consuming up to nearly 1 ton of coal per shift, and will do this work without any boosting.

These remarks apply to battery locomotives weighing from 15 to 20 tons (adhesive weight), as compared with steam locomotives of the 4-coupled type weighing about 25 tons. I am in possession of information showing that the average locomotive of the above type does not consume nearly 1 ton of coal per shift. A batch of 14 steam locomotives which I have in mind consume only 8 cwts. of coal per locomotive per shift ; but to be on the safe side we may add 25 per cent to this figure and call it half a ton. Under these conditions the locomotive will do nearly two shifts without boosting.

The same remarks again apply to the 4-axle double-bogie electric type weighing up to 35 tons, as it is possible to put double the battery capacity on a double-bogie as on a single-bogie locomotive.

*Cost of maintenance.*—I have previously quoted the figures given by Sir Vincent Raven for the maintenance of two straight electric locomotives. For a battery locomotive it is of course necessary to add to these figures the cost of maintenance of the battery.

*Running costs.*—The total cost for oil, grease and waste and cleaning materials for 16 months of an electric locomotive doing shunting work, running 700 miles and performing 35 000 ton-miles of shunting work, was £1 10s. Distilled water for the battery cost £1 12s. These two items covered the whole of the running costs, exclusive of wages.

*Repairs and renewals.*—Of the electrical equipment no renewals of any description were necessary, the only repair being an ammeter lead.

Of the mechanical parts, the brake shoes have been renewed once, at a cost of £4 10s. The wear of the brake shoes has since been much reduced by a more extended use of the rheostatic brake.

*Battery.*—The Chloride battery is guaranteed for two years, and after 16 months it shows no falling off, either in capacity or efficiency, and this is borne out by the fact that it will still work over its full range. The original setting of the ampere-hour meter fixing the proportion of the charge ampere-hours to discharge ampere-hours has not been altered.

The average annual cost of a standard 2-axle battery locomotive weighing 17 to 20 tons, as compared with steam locomotives of 22 to 25 tons, has been well within £15 per year for all maintenance costs, including repairs and small stores, such as oil, grease, etc.

# THE MEASUREMENT OF FLUX DENSITY IN THE AIR PATH OF A MAGNETIC CIRCUIT.

By W. P. Conly, B.Sc., Student.

(Abstract *of paper read before the* South Midland Students' Section, *7th March*, 1922.)

Summary.

A new form of magnetic balance has been devised for the accurate measurement of the intensity of field at any point in the air path of a magnetic circuit, the instrument being sufficiently delicate to detect differences in intensity of field amounting to one line per square centimetre, whereas existing methods measure only the average intensity over the whole field, or are only sensitive to differences of 150 to 200 lines/cm$^2$.

The distribution of the lines of force issuing from the sides of a bar magnet has been plotted and the surface of the magnet discovered not to be an equipotential surface.

Biot-Savart's law has been experimentally proved.

Attempts to measure with accuracy the flux density in the air path of a magnetic circuit have met with little practical success. There is an increasing necessity for more exact measurement of flux density in air.

The following well-known methods are in general use for measuring this quantity:—

(1) Flux meter method.*

(2) Faraday disc method.

(3) Bismuth spiral method.†

(1) The flux meter actually measures only the flux issuing from an electromagnet where the exciting current may be rapidly reversed.

In modern instruments the scale has 50 divisions on either side of zero. The linkage for one scale division is of the order of 10 000 maxwells. Thus it may be seen that if the pilot coil is composed of 100 turns of fine wire and if the flux in the magnet is reversed, then 1 scale division $= 10\,000/(2 \times 100) = 50$ lines.

Owing to the very slight controlling force acting upon the instrument the periodic time is of the order of 1 minute, so that it is very difficult for an observer to read the deflection to within 3 or 4 scale divisions without much practice. This means that under the above conditions it is difficult to read the total flux to within 150 to 200 lines, i.e. 6 to 8 per cent of the maximum.

In addition to these sources of error the flux meter is not accurate unless the resistance of the circuit containing the coil is maintained constant at the value used when it was calibrated, and this is seldom the case.

The following mode of procedure may be used for measuring the strength of the field of a permanent magnet.

The pilot coil is placed between the poles of the magnet, the plane of the coil being normal to the lines of force, and the deflection of the flux meter noted when the pilot coil is jerked away. This method, however, besides being clumsy, has a disadvantage in that it is difficult to ensure that only that flux which threaded it in its initial position is cut by the pilot coil.

(2) In the Faraday disc method a disc of copper is rotated at constant speed between the poles of the magnet the flux of which is to be measured, a brush being in contact with the spindle of the disc and another with its periphery. The voltage generated will depend upon the field strength and speed, as in any other type of dynamo. The speed being known, the field strength can thus be deduced. This method is liable to give inaccurate results, owing to mechanical difficulties.

Both the flux meter and the Faraday disc merely measure the total flux in a portion of the magnetic circuit, i.e. the sum of all the flux densities over a definite area. The flux density is then obtained from the expression:

$$\text{Flux density} = \text{Total flux}/\text{Area of path}$$

This is merely an average flux density and, although approximately correct for the iron portion of the magnetic circuit, it is not representative of the true flux density at any part of the air path. In the centre of the air-gap the lines of force are grouped together, whilst towards the edges they are dispersed and a fringe is formed so that considerable variations from the average are actually present but are not recorded by the method of measurement.

From this point of view the bismuth spiral is superior to both the previous methods as it measures the actual intensities at any point in the field. This method follows upon a discovery made by Hall in 1880, that if certain metals are placed in a strong magnetic field their resistance changes. The greatest effect is obtained with bismuth.

If the resistance of a strip of bismuth be taken before it is placed in the magnetic field, and the rise in resistance noted after it is so placed, the field strength may be calculated. Because of the very small increase of the resistance with a large increase of field, a change of field intensity of less than 1 000 lines/cm$^2$ cannot be measured.

Any instrument for measuring intensity of field must, to meet modern requirements, be capable of measuring not merely the real intensity from point to point in the field, but also minute differences in intensities, e.g. 50 lines/cm$^2$. Such an instrument has been constructed, based on the principle of balancing by a weight the force deflecting a short conductor placed in a magnetic field.*

---

* *Société Française de Physique*, Séances, 1904, p. 27, and *Electrician*, 1906, vol. 56, p. 560; also *Journal de Physique*, 1904, vol. 3, p. 696.

† *Comptes Rendus*, 1886, vol. 102, p. 358.

The author has lately constructed a new form of magnetic balance based on this principle, and this is illustrated in Fig. 1. A long balance arm of ash, AB, is delicately balanced by means of a pair of knife edges P in **V** grooves in the top of a brass column. At one end of the beam A is fixed a search coil consisting of 10 turns of silk-covered wire. This search coil is bent in the arc of a circle of radius $r = OA$, the sides $\alpha$ and $\beta$ being parallel. The side $\gamma$ is 1 cm long and radial. The two ends of this coil are carried along the beam and connected by means of two copper spirals S, $S_1$ to two terminals on the insulated collar E. These spirals are made of the finest wire which will carry 1 ampere and are rolled flat and annealed in oil, and they are placed as close together as possible without danger of touching. These precautions are necessary as it is essential that any tension or compression of the spiral shall have only a negligible effect upon the movement of the arm. The terminals on the insulated collar are connected to two terminals T, $T_1$, on the baseboard. At the point B on the other arm is hung a light aluminium scale-pan upon a pair of knife edges. A rider, d, slides along the arm OA to enable a fine adjustment of balance to be obtained. Immediately above the central knife edges is firmly fixed to the beam a small mirror, so that the ray of light from the lamp is reflected on to the scale Sc. Thus any slight deviation of the balance arm from the zero position can be readily and accurately detected. A small glass beaker, f, is placed round the scale pan to act as an air damper. The permanent magnet to be tested, PM, is fixed to the baseboard in such a position that the flux to be measured threads the search coil, and the lines of force are normal to the plane of the coil. This permanent magnet must be in such a position that the radial arm $\gamma$ of the search coil is always in the magnetic field when the balance arm swings. At the end B of the beam is fixed another coil, b, which will be referred to later.

From first principles, a wire 1 cm long carrying 1 C.G.S. unit of current is attracted or repelled by a field of unit strength (i.e. 1 line/cm$^2$) with a force of 1 dyne. The search coil consists of 10 turns. Thus if a current of 1 ampere flows round this coil in a certain direction, and the magnet has a field of unit strength, the length $\gamma$ of 1 cm is pulled downwards in a direction normal to its length with a force of 1 dyne. If weights are placed in the scale pan the arm can be brought back to zero. Thus the mass in the scale pan will give an indication of the field strength of the magnet. Now, since 1 mg weight = 0·981 dyne, if the ratio OA/OB = 0·981/1 then 1 mg in the scale pan will counteract the force of 1 dyne on the arm $\gamma$. Therefore if 1 mg on the scale pan is necessary to bring the spot back to zero position on the scale, the permanent magnet has unit intensity of field, i.e. 1 line/cm$^2$.

It might, however, be argued that the portion of the limbs $\alpha$ and $\beta$ in the magnetic field also carry a current and will also be deflected, but a closer examination will show that as these arms are parallel to one another, and as the current flowing along them is in relatively opposite directions, the effect of one counteracts the other and the only tendency is for them to be forced apart until the coil encloses a larger area. This tendency is, however, counteracted by the rigidity of the coil itself.

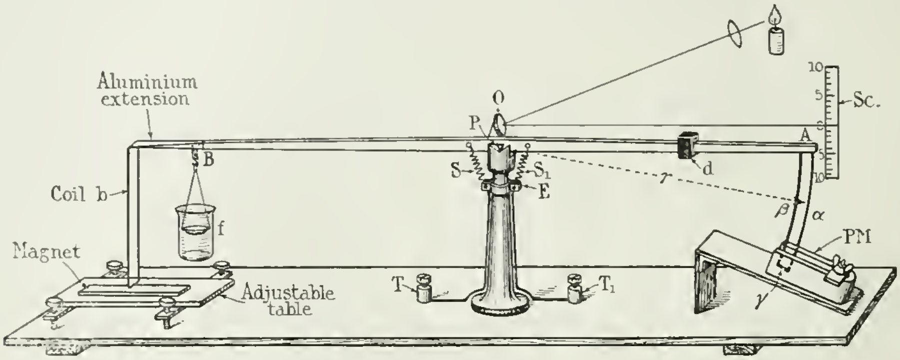


FIG. 1.

The short length of coil at A also carries a current and it might be thought that a serious error would be caused by the mutual action between this current and the stray field of the magnet. It is found in practice, however, that as this portion of the search coil is remote from the air-gap of the magnet, the leakage flux and the resultant error are negligibly small.

The instrument just described was constructed in the electrical laboratory of the Birmingham University, and is now being used as a laboratory instrument. By its use changes of field strength of 1 line/cm$^2$ may be detected with ease. As an example of its sensitiveness it may be stated that during one test upon a magneto magnet with an air-gap of 4 cm, a small nickel coin was suspended in the air-gap between the search coil and one limb of the magnet. Although the difference in the reluctance of the magnetic circuit caused by this slightly diamagnetic object was so small as to be usually negligible, yet the instrument registered quite an appreciable difference. As the instrument is so sensitive it is absolutely necessary that the current through the search coil be perfectly constant and accurately measured.

---

* A. GRAY: "Absolute Measurements in Electricity and Magnetism," vol. 2, pt. 2, p. 700.

The plane of the search coil must be absolutely at right angles to the flux in the air-gap, so that the maximum number of lines of force thread the coil. This may be accomplished by turning the magnet slightly until the scale registers a maximum deflection.

In the above-mentioned test it could be seen that the field was weaker in the centre of the air-gap than it was near either limb, thus showing that the lines of force spread out as they leave the magnet limbs, in the same manner as shown by the iron-filings method.

Finer adjustments may be accomplished by placing weights in the scale pan until an approximate balance is obtained, and then varying the current in the search coil until the spot of light returns to the zero position. Then the weight in the scale pan in milligrams, multiplied by the search-coil current in amperes, will give lines/cm$^2$ direct.

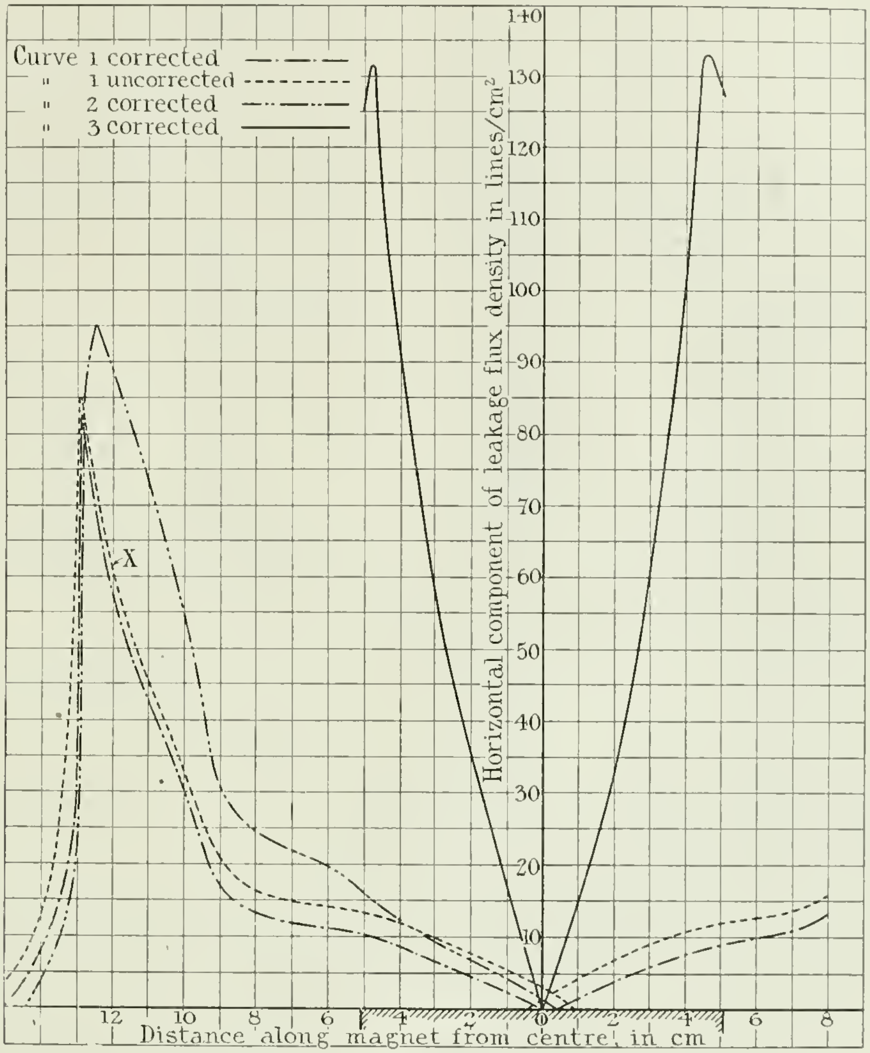


FIG. 2.

### TEST TO FIND THE DISTRIBUTION OF MAGNETIC FIELD ALONG THE SIDE AND EDGE OF A PERMANENT BAR MAGNET.

For this purpose a wooden wedge-shaped table is made, the surface of which is parallel to the search-coil arm $\gamma$ when the balance arm is in the same position. On the surface of this table is glued fine emery paper to prevent the magnet from slipping. The table is placed in such a position that the distance from the arm $\gamma$ to its upper surface when the instrument is balanced is half the width of the magnet. When the magnet is placed on its edge upon the table the arm $\gamma$ lies along the centre line of the magnet and as near to it as possible without actually touching it. This arm $\gamma$ now lies in the magnet field emanating from the magnet and is at right-angles to a certain component of that field. By passing a current round the search coil we can measure the strength of this component of the field in lines/cm$^2$ by the method described above.

If the lines of force leave or enter the magnet all along the surface at right angles, then the instrument reads direct in lines/cm$^2$ leaving or entering the magnet at the point under the seach-coil arm $\gamma$. The magnet can be slid up and down the table and a curve plotted showing the strength of field at every point along it. Fig. 2 shows such curves, curves 1 and 2 being attained for a magnet 25·5 cm long, 2 cm wide, and 0·5 cm thick. The abscissæ represent distances from the centre of the magnet, while the ordinates represent the strength of field emanating from the magnet at corresponding points. Curve 1 (not corrected) shows the readings along the side of a bar magnet.

The search coil, however, carries a current which produces around itself a magnetic field. Owing to the close proximity of the iron, the reluctance of the magnetic path of the field is affected. Since the tendency of any coil carrying a current producing lines of force is to move so that more lines will be embraced, the search coil moves down, thus covering more of the magnet. This downward movement is independent of the direction of the current, and can be taken as being constant all along the magnet as a low point on the saturation curve is being used. The value of this error, which might be called the "inductive effect," can be found for the working current of 1 ampere in the coil by replacing the magnet by a similar bar of unmagnetized steel. The inductive effect must be subtracted from the curve of field intensities. There is, however, another error which is not independent of the direction of the current, i.e. the error due to the earth's field, and its value may be determined by removing the magnet and reversing the current in the search coil. This error must be added to the uncorrected curve on one side of the centre and subtracted on the other. Thus a corrected curve is obtained of the flux density emanating from the side of a bar magnet, assuming that the surface of the magnet is very nearly equipotential.

In Fig. 2 at the point marked X there is a pronounced kink in the otherwise regular curve. This is probably due to the fact that at this point there is a slight "soft spot" in the magnet. The material at this spot being more permeable, a greater proportion of the lines of force due to this spot flow along the axis of the magnet, and a smaller proportion flow out at the side as leakage.

Curve 2 shows the corrected distribution along the edge of the same magnet. It is to be noticed that the intensity of field up to about 9 cm from the centre is far greater than is the case along the side of the magnet.

Curve 3 shows the case of a short bar magnet 4 in. × $\frac{1}{2}$ in. × $\frac{1}{2}$ in., where every care was taken in hardening and magnetizing the magnet to keep it homogeneous and uniformly magnetized. The magnetic moment of this magnet (found by the tangent galvanometer and vibration magnetometer method) is 1 377 dyne-cm.

Up to this point it has been assumed that for all practical purposes the flux along a bar magnet is normal to the surface. This being the case, the above curves, which actually represent the component of magnetic field normal to the surface, become curves representing the total intensity of field at any point along the magnet. To find how far this assumption is correct another test is required.

An aluminium extension, the length of which is adjustable, is fixed to the scale-pan end of the beam, and on the end of this extension is rigidly fixed a long rectangular search coil. The plane of this second coil, b (Fig. 1), is such that the length of the beam is normal to it. The length of this extension and the width of the coil are such that if the coil be placed in a field of 1 line/cm$^2$ and 1 ampere flows round the coil in such a direction that the coil is repelled, then 1 mg in the scale pan brings it back to its normal position.

A table of adjustable height is placed under this second search coil, upon which the magnet is laid. If in the position shown in Fig. 1 the lines of force leave the surface at an angle $\theta$, there will be a component $H \cos \theta$ of the lines of force tending to move the balance. If a current of 1 ampere flows in the search coil this force can be counterbalanced by putting weights into, or removing weights from, the scale pan. If there is no pull, then $\cos \theta = 0$, i.e. all the lines leave the surface at right angles.

Due, however, to the inductive effect of the search coil, a constant and known force must be applied to the remote end of the balance to tear the coil away. Measurements may be made by placing an assortment of weights in the scale pan, and then balancing these weights by means of the adjustable rider when the current is switched off. As the current of 1 ampere is now being caused to flow round the search coil, the force of attraction may be measured by taking weights out of the scale pan until the balance arm moves. This force of attraction consists of the resultant of the following three forces:—

(1) Force due to the inductive effect.
(2) Force due to the earth's field.
(3) Force due to the horizontal component of the magnetic field.

Forces (1) and (2) being known, the horizontal component of the magnetic field of the magnet may also be determined.

In practice it is found that the horizontal component is so small that it is impossible to weigh it except at the extreme ends of the magnet, in fact so small that for the purpose of determining the distribution of field intensity the lines of force may be taken as issuing at right angles to the surface of the magnet.

## PROOF OF BIOT-SAVART'S LAW BY MEANS OF THE MAGNETIC BALANCE.

Let a wire AB carry a current $I$; then the force on a unit pole placed at any point P due to a short elemental length of conductor $= df$.

$$df = \frac{I \sin \alpha \, dx}{y^2}$$

where $dx =$ elemental length of wire AB;
$y =$ distance from P to $dx$ at any instant; and
$\alpha =$ angle between P$dx$ and wire at any instant.

(This is generally known as Biot-Savart's law, but was originally stated by Laplace.)

Multiplying numerator and denominator by $\sin^2 \alpha$ we obtain

$$df = \frac{I \sin^3 \alpha dx}{y^2 \sin^2 \alpha}$$

Now $$r = y \sin \alpha$$

where $r$ is the perpendicular distance from the point P to the conductor; and the perpendicular cuts the conductor at C,

therefore $$df = \frac{I \sin^3 \alpha dx}{r^2}$$

But $$x = r \cot \alpha$$

where $x$ = length of wire from C to $dx$.

Substituting $d\alpha$ for $dx$ we have

$$df = \frac{-I}{r} \sin \alpha d\alpha$$

$$F = \frac{-I}{r}\int_{\pi/2}^{\alpha} \sin \alpha d\alpha \text{ (where } x = \text{CA and } \alpha = \text{angle CAP)}$$

$$F = \frac{I}{r}\Big[\cos \alpha\Big]_{\pi/2}^{\alpha}$$

$$= \frac{I}{r} \cos \alpha$$

$$= \frac{I}{r} \cdot \frac{x}{\sqrt{(r^2 + x^2)}}$$

If length CB = CA, then force $F$ on unit pole P due to whole length AB

$$= \frac{2I}{r} \cdot \frac{x}{\sqrt{(r^2 + x^2)}} \quad . \quad . \quad . \quad (1)$$

Thus for a wire of infinite length

$$F = \frac{2I}{r} \cdot \frac{\infty}{\sqrt{(r^2 + \infty^2)}} \text{ (for the whole length of wire)}$$

$$= \frac{2I}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

It is possible by means of the magnetic balance to demonstrate whether this formula holds good in practice. It is, however, impracticable to measure the force of attraction between two wires carrying a current when placed a distance $r$ apart; it is the force of repulsion which must be measured.

We have found that the force upon a unit pole placed at a distance $r$ from a wire of infinite length and carrying a current $I$ is $2I/r$ dynes.

This formula is in general use and is frequently wrongly applied to the case of a wire carrying a current, irrespective of the length of that wire. It has been previously shown that for a wire of definite length $2x$ carrying a current $I$ the force upon a unit pole placed at a distance $r$ from it is

$$\frac{2I}{r} \cdot \frac{x}{\sqrt{(r^2 + x^2)}}$$

By means of the balance the error caused by using formula (2) in place of formula (1) in the case of a wire 12 cm long has been found. The wire carried 50 amperes, and the search-coil arm was placed at a distance of 1 cm from it.

For the purpose of experimentally proving Biot-Savart's law coil b (Fig. 1) is used as in Fig. 3. The lengths of the two arms of the beam are such that if the width of this coil be 0·844 cm. then 1 dyne per cm length is balanced by 1 mg in the scale pan. In Fig. 3, AEFB represent the movable search coil; EF is bisected at O″; AB is bisected at O′; and CD is a wire 160 cm long. This length is such that leads connected to the ends of the wire do not appreciably affect the balance whilst carrying a current. The remote ends C and D of this wire are soldered to wire stretchers which keep it taut, and these slide up or down slots in the end brackets for altering the distance between the wire and the coil. A fine adjustment is made in this distance by means of a brass differential jack J fastened to the baseboard, whilst the inner screw of the jack is secured to the wire but insulated from it.

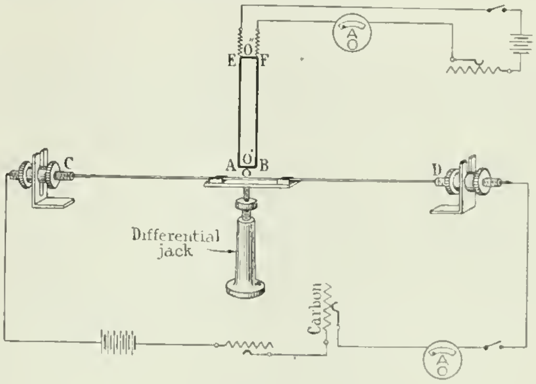


Fig. 3.

A steady current of 1 ampere is maintained in the search coil while currents varying from 0 to 150 amperes are sent along the wire CD. The leads from the search coil circuit are plaited together and taken to some remote distance before being connected to the ammeter and other apparatus, in order that they shall have no effect whatever upon the reading of the balance. For the same reason the leads from the wire are carried away as far as possible.

As the instrument is highly sensitive, extreme care must be taken. During recent experiments with this balance a mysterious inconsistency in results was definitely traced to the fact that the operator was carrying a thin steel nail-file in his pocket.

The theoretical force of repulsion may be calculated by means of formula (1) and compared with the result obtained in practice.

The arm AB (Fig. 3) is repelled by CD, but the arm EF carrying a current in a relatively opposite direction is attracted.

Let a force of repulsion be taken as positive, and let a force of attraction be taken as negative. The algebraic sum of the forces gives the resultant force. The effect of CD upon EA is balanced by the effect of CD upon FB.

*Calculation of the force upon the search coil.*—

Let
$$AB = EF = 0\cdot 844 \text{ cm},$$
$$FB = EA = 11\cdot 4 \text{ cm},$$
$$OO' = r = 1 \text{ cm},$$
$$CD = (OC + OD) = 160 \text{ cm}.$$

CD carries 50 amperes = 5 C.G.S. units.

(*a*) *Force on AB due to CD.*—According to the above theorem the field strength at the centre O′ of the coil side AB due to a current of $I$ amperes in CD would be

$$\frac{2I}{r}\cdot\frac{x}{\sqrt{(r^2+x^2)}}$$

where $x = CO = OD$, and $r = OO'$.

Owing to the displacement of any point on AB other than O′ the field strength will be a little different from the above, but calculation shows that these differences are so small with lengths such as AB and CD that they may be neglected, and the field strength along AB may be regarded as constant.

Thus
$$f_0 = 2\frac{5}{r_0}\cdot\frac{x_0}{\sqrt{(r^2+x^2)}} \quad (\text{where } r = 1 \text{ cm}, \; x_0 = 80 \text{ cm})$$
$$= 10 \times \frac{80}{\sqrt{(1 + 6\,400)}}$$
$$= 10 \text{ dynes per cm length (approx.)}$$

(*b*) *Force on EF due to CD.*—

$$\text{Force on } O'' = -2\frac{5}{12\cdot 4}\cdot\frac{80}{\sqrt{[(12\cdot 4)^2 + (80)^2]}}$$
$$= -\frac{10}{12\cdot 4}\cdot\frac{80}{\sqrt{(133\cdot 76 + 6\,400)}}$$
$$= -\frac{10}{12\cdot 4}\left(\frac{80}{80\cdot 93}\right)$$
$$= -0\cdot 796 \text{ dyne per cm length}$$

The total resultant force on the coil is + 10 − 0·796, or 9·204 dynes per cm length.

Fig. 4 shows curves connecting current in amperes with dynes per cm length, or weight in milligrams in the scale pan. Three sets of curves are shown and all are straight lines, proving that the force is directly proportional to the current. Dotted lines show calculated curves, while full lines show curves obtained from the readings of the magnetic balance.

*Sources of error.*—In all three cases there is a very slight deviation between the calculated curves and those obtained from the readings, but these inconsistencies can be accounted for.

Take as an example the case where $r = 0\cdot 75$ cm. It will be noticed that the calculated curve falls slightly above the curve given by the instrument (the measured curve).

There are several causes which would account for this. It is very difficult to measure exactly the distance between the centre of the wire and the centre of the arm AB. Two more calculated curves are drawn for $r = 0\cdot 7$ cm and $0\cdot 8$ cm, respectively.

The measured curve falls well between these limits, so that an error of much less than 0·25 mm in this measurement would give rise to this error in the measured curve.

Besides the difficulty of measuring the correct distance from centre to centre of wire and coil side the following sources of inaccuracy also arise :

(1) It is almost impossible to ensure that the corners at A and B are exactly square, so that the effective length of the arm AB may be shorter than its apparent length.

(2) The arm AB may not be exactly parallel to CD.

A dotted line is drawn showing the effect produced if the projected length of the arm AB upon the wire CD = 0·83 cm. It is found that this dotted line almost coincides with the measured curve, showing that the latter would coincide with the calculated curve if, owing to either source of in accuracy given above, the projected length of AB upon CD = 0·83 cm.

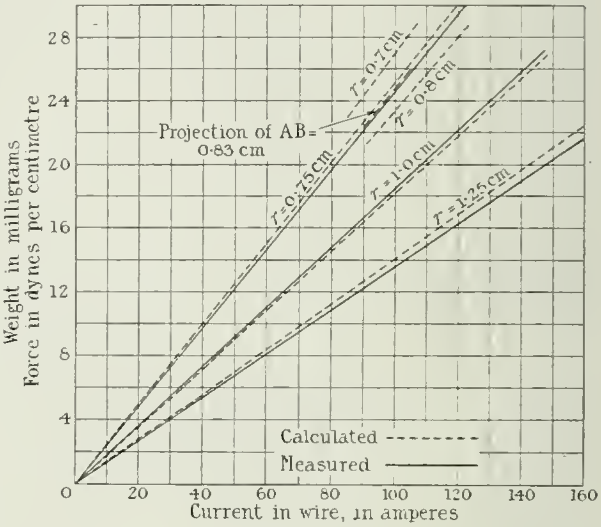


FIG. 4.

Although every care was taken during the experiments to avoid such errors, the methods of measuring lengths such as AB and $r$ do not admit of an accuracy compatible with the sensitiveness of the instrument, but the result appears to afford good evidence as to the validity of the expression

$$F = \frac{2I}{r}\cdot\frac{x}{\sqrt{(r^2+x^2)}}$$

The author is greatly indebted to the University of Birmingham, where he was given every facility for carrying out the experiments necessary for this paper. He is particularly indebted to Professor W. Cramp, D.Sc., who so kindly allowed him to be his assistant in his research upon magnets and whose untiring advice and guiding hand made this work possible.

# ELECTRICITY AS APPLIED TO MINES.

By J. C. Stewart, Student.

(Abstract *of paper read before the* Scottish Students' Section, 10*th March*, 1922.)

### Summary.

The paper deals in a very general way with the use of electricity in collieries. The types ot generators, motors and cables are explained, and the factors governing the use of each particular type are discussed.

A brief outline of the mechanical plant used in conjunction with motors is given, including pumps, haulages, coal cutters and winders.

Diagrams are given of a typical haulage, as used extensively in this country, a turbine pump, a disc coal cutter and a small electric winder.

### Introduction.

For the past few years the ordinary individual has had brought to his notice phases of industry which before he was wont to regard as necessary but noxious. This applies very truly to the coal industry. More recently the eyes of the community were focussed on the coal mines and a more general knowledge of the mining industry and its absolute necessity to the life of this country was then gained. In the present period of economic unrest and bad trade every industry is trying earnestly to cut down costs and increase efficiency, and in this project they have no better ally than electricity.

But for electricity, coal mines would be of no value to us. Since the earliest days of coal mining the use of machinery has slowly but surely ousted purely manual labour, as in most other industries. The problems presented by winding, pumping, ventilation and haulage have been very gradually solved to the satisfaction both of engineers and workers.

Twenty years ago the use of electricity was confined to lighting on the surface and to long-distance underground signalling with batteries. To-day there is not a single instance in the application of power where electricity has not been employed, in most cases successfully.

By far the greatest number of collieries have direct-current installations, owing to the fact that the common load in pre-war days was in the neighbourhood of 300 kW and an installation of this kind is cheaper with direct than with alternating current. The tendency at the present time is, however, where possible, to take a bulk supply; where the power companies have not run mains and where there is a fairly big demand for power, turbo sets up to 5 000 kW have been installed.

Voltages vary from 80 to 550 with direct current and from 400 to 6 600 with alternating current, and periodicities with the latter are 25, 30, 40 and 50.

Generally speaking, an a.c. system is to be preferred to a d.c. system. With the former, it is easier to comply with mining regulations if the mine is liable to gas. Direct-current motors, on the other hand, are more liable to open sparking and for this reason in fiery mines they have to be totally enclosed. This is practicable up to about 40 h.p., but above this the overall dimensions become abnormal.

In the case of a.c. motors, enclosure is necessary only at the slip-rings, while squirrel-cage motors can be left open.

An ideal system is a combination of both alternating and direct current, but this is not always possible.

### Motors.

All types of motors in use for industrial purposes are, generally speaking, employed underground; they are modified, however, to suit the conditions. The overload capacities are extended, for the motors may have to be explosion-proof and withstand damp atmospheres.

Again, although laid down in places where they will be protected, they encounter troubles not associated with surface plants. The men in charge cannot always make systematic and regular visits to all the motors, as in some cases they are so widely distributed, and the attendants are usually kept busy with actual repairs.

In fiery mines or those liable to gas, motors and switchgear must be flame-proof to lessen the possibility of danger from explosions by sparking. Mining regulations are becoming very stringent in this matter and it is not always permissible to install electrical plant where the possible danger from gas is very great.

To overcome this, the inclination is towards the use of alternating current, when the risks from open sparking are considerably lessened. Motors are placed, where possible, in intake airways, i.e. where the fresh air is entering.

### Switchgear.

In common with motors, mining switchgear when underground follows the lines of ordinary switchgear. The same laws governing the installation of motors apply equally to switchgear. Switches have large machined faces where joints occur, are as far as possible fool-proof, and must have plenty of space inside, to lessen any risks of short-circuits or earths caused by damp or deposit.

The human element, in a great many cases, is largely responsible for the success or failure of electrical plant underground. The man in charge of, say, a haulage or a coal cutter is usually more concerned in keeping up his production than in shutting down for the electrician to repair any small trouble, and this usually leads to more serious breakdowns.

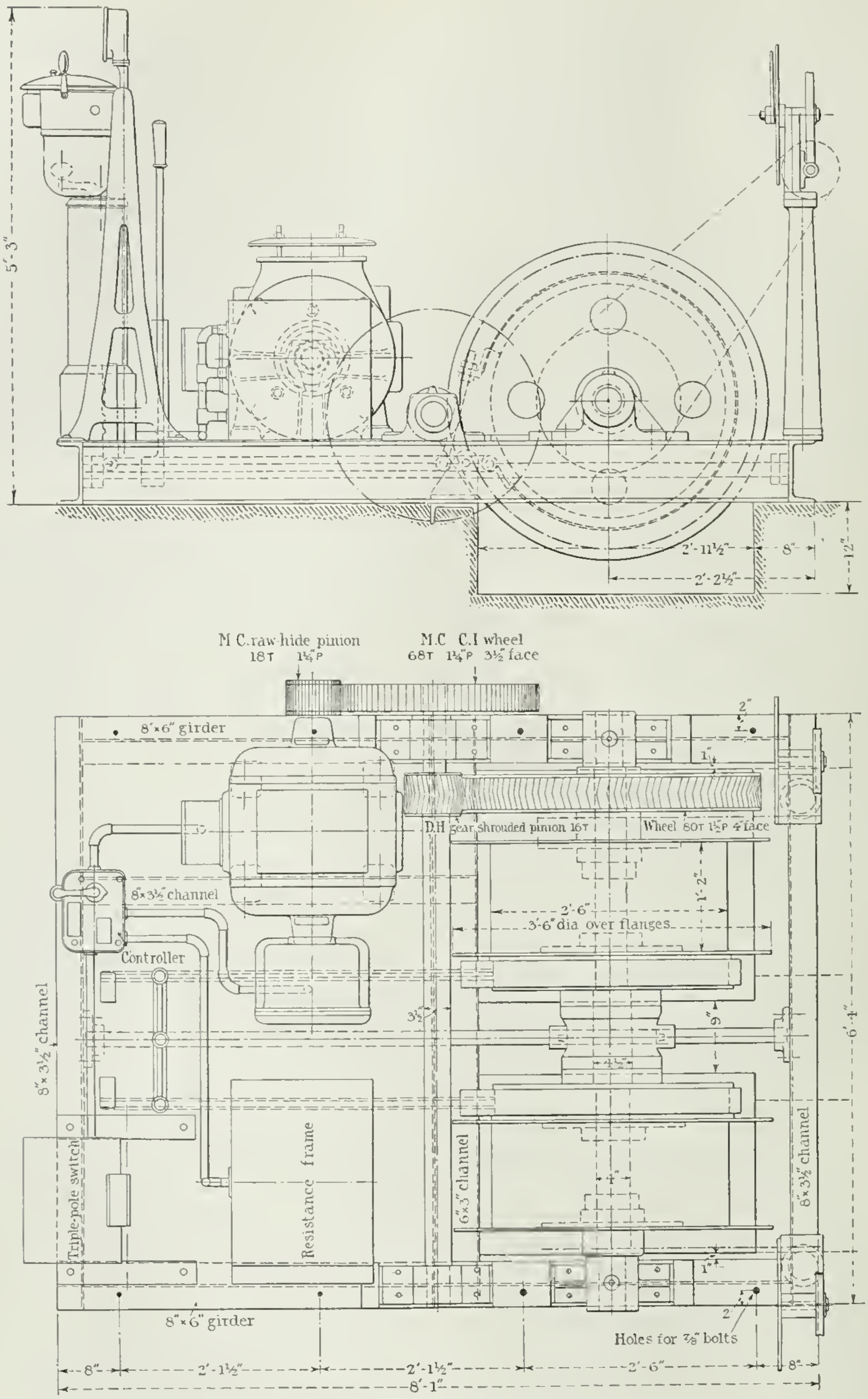


FIG. 1.—Arrangement of 250-h.p. main-and-tail haulage.

### PUMPING.

In all the uses to which the motor has been put in mining, no better results have been obtained than in the driving of pumps, as they have to operate in some cases where no other power than electricity could be used efficiently. Both reciprocating and turbine pumps are in use for mine drainage, but of late years the turbine pump has become more prominent, the determining factor for this being largely the small amount of space occupied and the advent of multi-stage pumps. The time is past when turbine pumps were considered suitable for low lifts only, as any required head can now be obtained.

A brief description of both types of pumps would perhaps be appropriate here. A reciprocating pump consists of three separate single-acting plunger pumps connected to common suction and discharge pipes. The cranks on the shaft are placed 120° apart, so that the discharge is practically continuous. Occasionally, however, separate suction and discharge pipes are built with the pump, so that if one plunger pump breaks down it is possible to carry on with the other two until repairs are effected. The speed of the rams varies from 35 to 60 ft. per minute, and to obtain this the motors require to be geared down.

The turbine pump is made up of a series of single-stage centrifugal pumps. Each rotating disc or impeller has its own chamber. The water, after leaving the first impeller, passes through a guide port to the second, and so on until it reaches the delivery column. The head generated depends upon the peripheral speed and diameter of the impellers, the best speeds being from 1 000 to 3 000 r.p.m.

For turbine pumps, alternating current is to be preferred for high speeds and large horse-powers, but there are quite a number of direct-current motors running up to 1 800 r.p.m. which is about the limit, as commutation troubles become considerably increased at higher speeds.

The limiting feature with direct current is, as mentioned above, the necessity for enclosing a motor on account of gas in the mine. To avoid this, it is usual to install two or more pumps of smaller capacity and divide the total lift into two or more stages.

With alternating current, squirrel-cage motors are much used, and it is not an infrequent practice, where there are large quantities of water to be dealt with on a fairly high head, to install high-tension or even extra-high-tension motors for driving pumps.

### HAULAGES.

The conveying of material from the coal face to the bottom was a problem which until recent years was not satisfactorily solved. The advent of larger electrical installations, however, has resulted in a marked tendency towards electrical haulage for the large plants on the surface, while for secondary haulages underground electricity has, of course, no rival.

The methods of haulage may be divided into the following: Direct-acting haulage, main-and-tail rope haulage and endless-rope haulage. To this might be added endless-chain haulage and haulage by locomotive, although these latter do not find much favour in this country.

The features determining which type shall be used are the circumstances existing at each particular colliery, and it is quite common to find more than one system in operation at the same colliery.

In the direct-haulage system, the motor and haulage gear are placed at the top of the incline, the full hutches are drawn up the incline by the haulage, and the empties are afterwards run back down the gradient, carrying the rope with them. The inclinations must be sufficient to ensure this, e.g. up to 1 in 20, and must be fairly uniform. One line of rails is used, though a double-drum haulage and double rail can quite well be used. The average speed is about 6 m.p.h.

The main-and-tail haulage is generally used on varying gradients, where it is necessary to haul the hutches both inbye and outbye. Two drums are used, both being fixed to the same shaft and driven by clutches, one carrying the main rope and the other the tail rope. The load of full hutches is drawn out by the main rope, the tail rope being fixed behind the rake. Both drums revolve at the same time, one being driven by the motor direct and the tail drum being turned by the tail rope as it is drawn off. If the gradient at any part of the road favours the load, the main rope is detached and the load allowed to run forward by gravity, but controlled by the brake on the tail drum. When the load is brought out, empty hutches are attached and hauled inbye with the tail rope, the main rope being now used for the control. Speeds up to 10 m.p.h. are usual with this type.

The endless-rope or chain haulage has one chain or rope running over the entire system of both sets of rails, one set going in and the other out. The hutches are sometimes attached singly about 10 yards apart, and sometimes 8 or 10 of them are fixed on to the rope together.

Haulage by locomotive is so closely allied to tramway haulage or traction that it needs no description. It is greatly used in America where the inclinations of the seams are not quite so steep as in this country.

### MOTORS FOR HAULAGES.

All types of motors are in use with haulages, depending, of course, on the system of supply. Whatever the type, it has a large overload capacity and a fairly high rating. Series motors are sometimes used, but compound-wound motors are most generally installed if the system is a direct-current one. In the case of an a.c. system slip-ring motors are usually the type most in favour owing to the large starting torque required.

The resistance coils on the starting gear must be capable of withstanding full-load current for several minutes, as in some of the roads with steep gradients there are bad bends to be encountered, and these necessitate the slowing down of the motor.

### COAL CUTTING.

The practice of working coal seams by machinery is one that has become necessary for several reasons. For instance, it is more profitable to work thin coal seams by mechanical than by manual labour. The thickness of coal seams varies from 12 in. to about 6 ft., although there are few seams of the latter thickness left in Scotland. The average thickness is 24 in. and this is therefore the chief determining factor in the height of a coal cutter.

The length of face is usually about 100 yards, and this is split up by roads or gates every 10 yards or so. The cut is generally made under the coal to a depth of from 3 to 6 ft., and about 5 in. thick. Sometimes, however, better results are obtained by cutting in the coal if the underlying strata be too hard, and if the coal is very hard it is usual to cut in any soft band which appears in the coal. The coal is then parted from the upper strata by blasting or hand labour, filled into hutches and taken away. This method is known as the "long-wall" system of coal cutting.

Another method, largely used in England, is the stoop-and-room or pillar-and-stall system. This is only carried out where the coal seams are fairly thick, e.g. 4 ft and upwards. In this method the coal is cut into rectangular pillars or stoops by stalls or rooms driven at right angles to each other, the pillars or stoops being afterwards taken out.

It is not possible to lay down hard-and-fast rules as to methods of working coal, as circumstances vary with each seam, and each particular stratum of coal has to be considered on its own characteristics.

At the present day there are three distinct types of coal cutters in successful operation, viz. the disc, the bar and the chain. The oldest of these is the disc machine, which might be described as an adaptation of the circular saw. The disc or wheel has cutting tools or picks fixed on its periphery. The disc is supported from the general body by a strong bracket so that the cutting portion projects to the required amount. The body of the coal cutter consists of a motor, gear-box for driving the disc, haulage drum and gear, and starting switch. These are all encased in strong steel boxes and mounted on skids or a base-plate extending the full length of the body. By reason of its general robustness and massive construction, this type of coal cutter is capable of doing harder work than the chain or bar type.

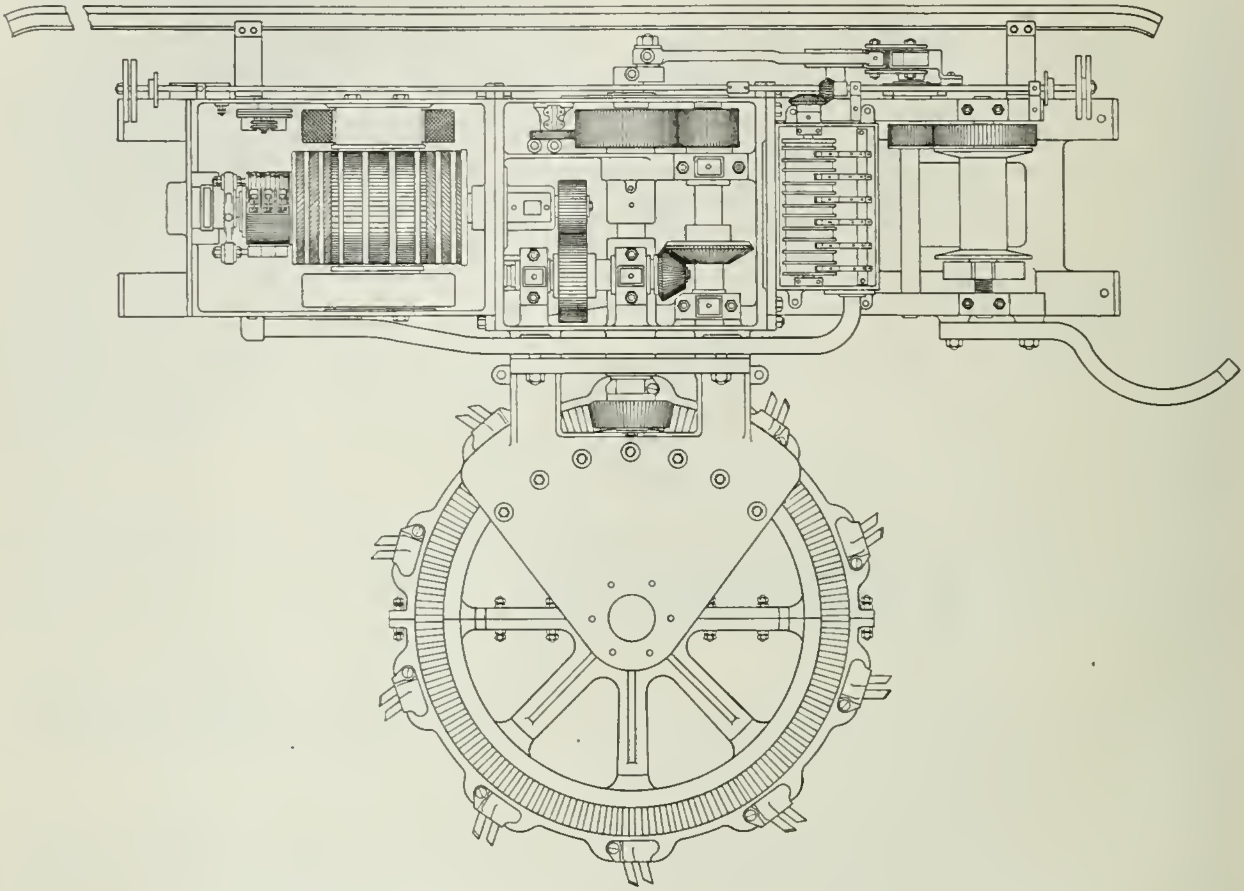


FIG. 2.—General arrangement of the "Crescent" coal-cutter; B type with d.c. motor.

Bar coal cutters differ from both the disc and chain types in their cutting action, in so much that the bar might be likened to a taper twist-drill in the threads of which picks have been fixed. To this bar is given a revolving, reciprocating motion. Due to this reciprocating motion, part of the holings work their way out

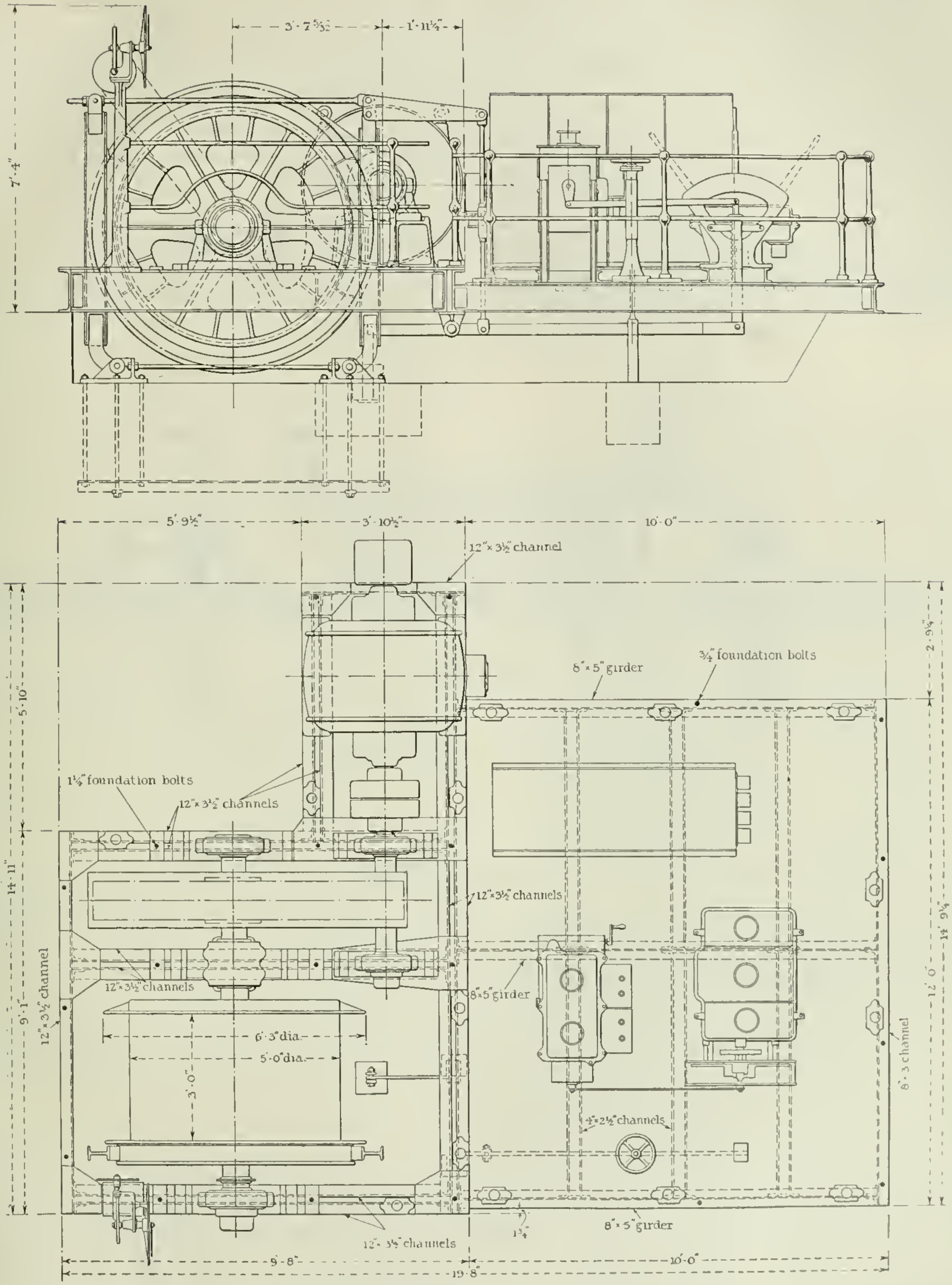


FIG. 3.—Arrangement of 150-h p. haulage gear.

along these threads. Where the coal is at all friable the bar machine gives wonderful results and a much higher speed can be attained by the actual picks.

Judging from old records, it appears that the chain machine claims priority for the number of patents taken out in connection with it. It has a jib carrying a heavy, case-hardened endless chain with a pitch of about 7 inches. The cutter picks are fixed in recesses in shaped cutter blocks on the chain, and are held in position by set-screws. The chain is carried round a sprocket wheel, the centre of which is hollowed out to form an oil reservoir for the wheel. The tension of the chain can be varied by an adjusting screw and the jib locked securely in position. Within late years there have been more of this type of coal cutter installed than of the bar or disc type, a fact peculiarly significant of the practice necessary in collieries at the present day.

Electricity was first applied to coal cutters about 30 years ago. Motors of from 10 to 12 h.p. were fitted, but the attempt was a complete failure, which is not surprising considering that motors of 28 to 40 h.p. are used to-day, and even these are not sufficient in some cases. The motors are, of course, of the totally enclosed type. For use with direct current they are four-pole and doubly compounded. Some makes have series fields which give them a very heavy starting torque, but the armatures all run about 1 000 r.p.m. and are geared down to the disc, chain or bar.

In alternating-current installations for smaller sizes of coal cutters, squirrel-cage motors are fitted and, for heavier machines, wound rotors. Due to the small amount of height permissible in coal cutters the armatures and rotor cores are very long with small diameter. In addition, a reversing switch is carried, and the starting switch and resistance are of heavy construction as they usually have to withstand a great deal of "inching."

### WINDING.

While there have been a number of cases where electricity has been applied successfully in place of steam, there is not the same chance for economy as in most other branches of mining work. Very little would be gained in most cases by substituting electricity, the chief difficulty being the large mass which must be started from rest, accelerated often to 60 ft. per sec. and brought to rest in less than 90 seconds. Added to this is the fact that the motor in a great many cases would be in the region of 1 000 h.p. and would have to compete against a steam engine applied directly to the work and in close proximity to the boilers.

In addition, the demand for anything up to 1 500 h.p. at short notice would be somewhat difficult to cope with, although the advent of super-stations would make this factor of little account. Despite this, electricity has been tried out in quite a number of cases and there are now both d.c. and a.c. winding installations. The motors are of the open type, running at normal speeds and controlled by heavy reversing switches, and have to be capable of severe overloads.

The main advantages of electric winding are that maintenance is considerably less than for steam, smaller pit-head frames are needed, and economical operation is obtained in the period taken by the colliery to reach its full output.

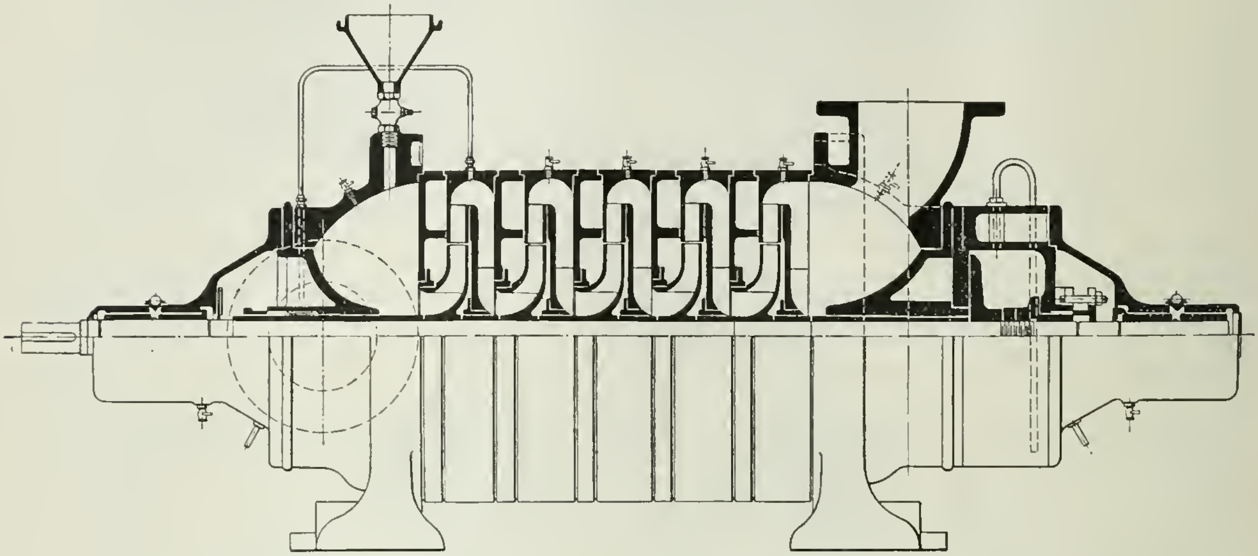


FIG. 4.—Sectional arrangement of multi-stage turbine pump.

### VENTILATION.

This is the most permanent load of any in mining work and, for this reason, fans should all be electrically driven, in order to improve the net load factor of the plant. This is even more so at the present day when most collieries employ the smaller high-speed centrifugal suction or force fans very suitable for direct coupling to a motor, instead of the large Guibal fans of former days, which would require a large low-speed motor for their operation. Added to this is the fact that when a colliery is first opened (and for several years afterwards) the full air delivery is not required, and electrically driven fans can be run at lower speeds without undue losses.

For ventilation work a.c. motors are preferable, although there is no reason why d.c. machines should not give satisfactory results. A synchronous motor is eminently suited for this work, as the load is constant.

Miners are gradually losing their fear of electrical breakdowns, and for this reason we may expect that in the future very few steam ventilating fans will be installed.

The three following applications of electricity in mines have now reached the stage where at least one of them has no competitor, the other two being impossible without electricity, viz. shot-firing, telephones and signalling.

For the first-named, a small magneto exploder is generally used, although some managers still favour a battery of cells. The magneto armature is hand-driven through gearing at from 2000 to 3 000 r.p.m. at the moment of closing the firing key. Both low-tension and high-tension exploders are in use, and series connection ensures that no part is fired unless all the fuses are in order.

Telephone connection is now legally enforced between the generating station, pit head and pit bottom. The telephones are the same as in general commercial use, but care is taken to make them very strong and watertight.

For signalling circuits large batteries are installed with a maximum voltage of 25. Enclosed pull-switches are installed every hundred yards, and thus any danger of open sparking is eliminated. Signals are indicated both visually and by means of a bell, so that the risk of receiving the wrong signal is checked. Arrangements are made to prevent confusion of signals, the signals being automatically returned to the sender so that mistakes can be rectified.

### Lighting.

Both carbon and metal filament lamps are used for lighting the pit bottom and for 100 yards from the bottom, but at the face Davy lamps still predominate. A recent report showed that there were 4 300 electric hand-lamps and 720 000 oil hand-lamps in use.

The efficient lighting of working places underground helps to increase both the output and the safety of working. Electric hand-lamps consist of an aluminium case in which is a lead storage cell. The lamp itself is further protected by a thick glass cover. The casing is so arranged that if the outer glass cover is broken the lamp is automatically extinguished. The Home Office regulations require that at least 1 c.p. must be given after 9 hours' continuous burning.

There are various makes in use, but they differ very little in principle. The usual weight is about 4 lb.

The objection that electric lamps give no indication of fire-damp has been overcome by the introduction of various fire-damp detectors. One make gives indication of as little as 0·25 per cent of gas.

### Miscellaneous.

One other piece of machinery largely in use in collieries now-a-days is the shot drill. This consists of a rotary drill driven by a 4 h.p. motor, and the whole carcass is fixed on wheels so that it can be moved quickly from place to place.

These machines are used chiefly for drilling holes in the coal after it has been cut by the coal cutter. In these holes are placed explosive cartridges which are fired, the coal consequently being blown down.

The following are some figures in connection with a fairly large colliery in Scotland, and these figures are fairly typical for the whole of Scotland :—

| | |
|---|---|
| Output per week .. .. .. | 8 200 tons |
| Consumption per week .. .. | 67 000 units |
| Water used per week .. .. | 32 000 tons |
| Water per ton of coal .. .. | 4 tons |
| Consumption per ton of coal .. | 8·2 units |
| Average load factor .. .. | 44 per cent |

The overall output is 6·5 lb. of coal per unit generated.

# HYDRO-ELECTRIC POWER SUPPLY.

By A. Tustin, M.Sc., Student.

(Abstract *of paper read before the* North-Western Students' Section, 14*th February*, 1922.)

## Summary.

The objects of the paper are: (1) To describe briefly the chief constituent parts of a hydro-electric development, and their functions; (2) to discuss some of the economic factors controlling the development and operation of water-power plants; and (3) to consider the question of tidal power where it exemplifies the working of these economic factors.

## Types of Development.

A stream of water, in which $Q$ lb. of water per second flow so that they fall through a vertical head of $H$ feet, necessarily loses $QH$ ft.-lb. of potential energy per second. In the state of nature this is turned into the kinetic energy of irregular motion, and by fluid friction into heat. The task of the water-power engineer is to reduce fluid friction by guiding the water into a uniform stream-line flow, and abstracting its energy by means of water turbines.

A given power may be provided either by a small stream of water falling through thousands of feet, or by an immense mass of water falling through a few feet. There is no real difference between the principles by which the water-power engineer deals with the one or the other, but naturally they lead to plants widely differing in engineering structure and appearance.

No two water-power stations are identical, owing to local geography, the power available, and the constant progress in technique; but for descriptive purposes we may distinguish two characteristic types of plant, i.e. low-head plants of the dam or barrage type, and higher-head plants of the pipe-line type. The two merge into each other.

In the dam type the power house itself is built across the river so as to form a dam, or part of a dam. The water rises on the up-stream side, and is allowed to flow through turbines in the power house under the head so obtained.

In the pipe-line type the water is accumulated in a catch pool at a higher level, and is brought down to the power house by a pipe or pipes, which may be miles long.

## Pressure Pipe or Penstock.

The design of pipe lines for hydro-electric work presents a very varied series of problems. There is a wide choice of material: riveted boiler plate, reinforced concrete, wood staving, cast iron, welded steel and weldless steel all being met with.

The number, size and location of the pipes must be determined, and due thought given to the questions of anchorage, temperature expansion, water-hammer effects, and mechanical strength, both as a beam and whilst partly filled or under sudden suction due to increase of load.

Actually pipes are met with, varying from more than 12 ft. in diameter and some $\frac{3}{8}$ in. thick at low heads, to a diameter of 19 in. and $1\frac{3}{4}$ in. thickness of weldless steel, as in the 5 000-ft. head pipe-line at Lac Fully, in Switzerland.

The water pressure upon the interior of the pipe increases proportionally to the head as the pipe descends from the forebay to the power house. For this reason long pipes are sectionalized, and the material, size, thickness and, occasionally, the number of pipes, are varied so as best to suit the conditions of each particular section.

With regard to the choice of the number of pipes to convey a given quantity of water, the best practice is to make the number as small as possible, often using one only. This may be seen by considering that the total section of the pipes is kept unchanged while the number is varied. The smaller pipes will not need to be so thick, both thickness and diameter being proportional to $\sqrt{(1/n)}$, where $n$ is the number of pipes. The area of metal per pipe is therefore proportional to $1/n$, and the total metal $n \times (1/n)$ is unaltered. At the same time, however, the efficiency of the pipe is decreased, as the frictional loss of head, being roughly proportional to the wetted surface, is increased by using a number of small pipes.

In practice more than one pipe is used, and sometimes as many as five or ten. This is sometimes due to the fact that the installation is made step by step, or to manufacturing, transport, or erection considerations. For pipe lines up to a few hundred feet in length it is a common practice to put one pipe to each turbine, thus giving reliability and avoiding the losses inherent in the distributor pipe which would otherwise be necessary.

## Choice of Diameter.

The basic principle upon which all economical design depends is that an additional small investment of capital upon any part or item of the plant should give the same return, and that that return should be equal to the market rate of interest on this investment, plus the annual depreciation on this investment at a percentage suited to the item in question, plus an allowance for profit.

In this case an increase in the diameter of the pipe would result in a definite additional capital outlay. It would result in a gain because the decrease in the frictional loss would render an equal amount of energy saleable, and the gain would be the sale price of this energy. It would also result in a loss because the turbine and the generator would have to be correspondingly larger, working at a slightly higher head because of the decrease in the frictional loss.

The annual value of the energy gained should be just sufficient to pay for the interest, depreciation, and profit charges on the increase in cost of the pipe and the increase in cost of the generating unit. This consideration enables an economic limit to be arrived at.

### Water Turbines and Specific Speed.

In practice only two types of water turbines are generally used, the Pelton impulse wheel, best for small powers and high heads, and the Francis reaction turbine, best for large powers and low heads.

The conditions determining which type is the more suitable for a given case are largely summed up in the specific speed, which depends solely upon the geometrical proportions and shape of the wheel, and not upon its size.

If a runner of given geometrical form be placed under a given head there will be only one speed at which the velocity of flow of the water and the velocity of the blade are so related that the water enters without shock and leaves with low velocity, and therefore only this speed will give the best efficiency. The spouting velocity of water at a head $H$ is proportional to $\sqrt{H}$, and, therefore, keeping the turbine always running so that the water enters without shock, the velocity of the blades must be proportional to $\sqrt{H}$ and the speed (r.p.m.) to $\sqrt{H}/D$.

The power developed is the product of the quantity of water and the head, i.e. it is also proportional to $\sqrt{H}D^2H$, since the area of the water passages for geometrically similar wheels is proportional to $D^2$.

We have then the two proportions :

$$N \propto \frac{\sqrt{H}}{D}$$

and

$$P \propto H\sqrt{H}D^2, \text{ or } D \propto \frac{P^{\frac{1}{2}}}{H^{\frac{3}{4}}}$$

Eliminating $D$, we have

$$N \propto \frac{H^{\frac{5}{4}}}{P^{\frac{1}{2}}}$$

or

$$N = K\frac{H^{\frac{5}{4}}}{P^{\frac{1}{2}}}$$

where $K$ is defined as the specific speed.

Pelton wheels have specific speeds of less than 5 or 6. Francis turbines have specific speeds of from 15 to 125. Intermediate values may be obtained by using more than one Pelton wheel mounted on the same shaft, or wheels with more than one jet. Since for a given turbine speed the specific speed must vary as $\sqrt{P}/H^{\frac{5}{4}}$, it will be seen how the head and power determine the choice of type of wheel.

### Draught Tube.

The draught tube is an integral part of the turbine, as it is used to recover the energy represented by the head which the water retains when leaving the turbine, and the energy due to the velocity with which it leaves the turbine.

### Headworks and Forebay.

The forebay at the head of the pipe line has two main functions :—

(1) To supply water capacity to meet a sudden change of load, as the water in a long canal or flume cannot quickly adjust its flow to new conditions. If no capacity were provided at the forebay a sudden increase of load would drain the forebay, and a sudden decrease of load would cause it to overflow, owing to the inertia of the water running into it.

(2) To remove foreign bodies from the water, the water velocity is reduced so that sand and grit settles, and straining racks (trash racks) are provided, first of coarse and then of fine mesh.

### Storage and Regulation of Flow.

There are really two distinct reasons for providing hydro-electric plants with water storage, as follows :—

(1) During any day the mean power which may be generated is proportional to the total flow of water. For most purposes, however, the load curve is peaked, and the flow of water must follow the peaked load curve, and if the whole of the available water is to be used, some of it must be stored at times of low load, so as to be available for times of peak load. This storage is sometimes called "pondage," and is often placed at or near the forebay, so that the works above the forebay may be designed to meet only the mean load, not the peak load.

(2) Storage from wet to dry parts of the year, and from dry to wet years. The whole problem is very similar to that of ordinary town water-supply, but is usually on a larger scale. It is worth noting that storage at the head of a river serves for the seasonal regulation of all water-power stations farther down the river. This is one reason, amongst several, why the water development of a river must be considered as a whole, i.e. as one problem from source to mouth.

Two factors largely decide the desirability of storage, the first being the head at which the plant works. A given quantity of water stores an amount of energy proportional to its head. For example, a 10-ft. cube of water at a head of 5 000 feet represents about 120 kWh, but at a head of 20 feet represents only about 0·5 kWh. For this reason high-head plants are provided with storage wherever the ground permits, but low-head plants never have storage.

The second factor is the frequency with which the reservoir is filled and emptied. Clearly, the mean power from a given storage is proportional to this. This is the reason why daily pondage presents so few problems, as compared with seasonal storage. It is also the reason why storage from dry to wet years is practically never found, and why a district with two wet seasons favours storage more than does a district with only one.

### Storage for Tidal-power Regulation.

These two principles have an interesting application in schemes for developing tidal power, where the problem of fitting a peaked power-supply curve, with its peaks at variable hours of the day, to a peaked but stationary demand curve is probably not capable of a very cheap and easy solution. It has been suggested that a high-head storage reservoir should be established near the tidal power station. At times of excess power it would be used to pump water up to the reservoir. This water would be run out to supplement the tidal power when required, special high-head turbines being provided.

This regulation by pumpage is not untried ; there is a small river station at Walker Burn on the Tweed so regulated with a 1 000-ft. head reservoir, and a larger one at Vouvry in Switzerland working at 3 000 ft.

There are three separate frequencies to be considered in the case of tidal power :—

(1) The tidal power, utilized on rise and fall, has a peak every 6 hrs. 12½ mins.
(2) The load curve has a peak every 24 hours.
(3) The tidal power available is four times as large at spring tides as at neap tides, with peaks every fortnight. If the actual cost of the high-head reservoir were very large, as seems likely to be the case, it might be profitable to store for the high-frequency variations, but not for the low-frequency variations, i.e. it might be more economical to turn the tidal power into constant available power without providing storage to distribute this power over a commercial load curve with a correspondingly higher peak value, and similarly it might be profitable to develop fully the neap tide power and neglect the excess at spring tides.

### Interconnection and Storage.

When power plants are fed by streams having a different variation of flow with the seasons, as when one is fed by melting snow and the other by rainfall, they may be electrically interconnected, and the seasonal storage required is thus reduced. Similarly, on tidal-power development schemes it has been suggested that the power from estuaries having different tidal times, when fed into a common network, might be arranged to avoid or diminish storage. Such schemes have been proposed for the Severn and the Dee ; and for the Forth, Clyde, and Solway Firth.

### Tidal Power.

When the tide rises, work is done in lifting an immense mass of water against gravity. The rate at which work is done, i.e. the power, is enormous. It has been estimated, for instance, that the Irish Sea absorbs at times anything up to 6 000 million kW. In the open oceans the greater part of this energy is restored on the fall of tide, the tidal heap or wave simply swinging round the earth. Shallow seas and narrow places absorb a large quantity of tidal energy in friction, which is supplied by a corresponding decrease in the rotational energy and speed of the earth. Since this energy of rotation is sufficient to supply 1 000 million continuous kW for 800 million years, neither the immense tidal losses nor such trivial additions to them as any human harnessing of the tides might make, will cause any perceptible lengthening of the days and nights during any period of immediate interest to us.

During the past few years there have been a number of schemes for turning the tidal power to account. These are of two main types. The first consists of a float or floats rising and falling with the tide, and coupled by cranks, for instance, to apparatus on shore. This scheme cannot be expressed correctly in figures, for if we take a float of 1 000 tons' displacement on a 20-ft. tidal range, the power would be only 1·4 kW, as follows :

Energy every 12 hours $= 20 \times 1\,000 \times 2\,240 = 4{\cdot}48 \times 10^7$ ft.-lb.

$$\text{Power} = \frac{4{\cdot}48 \times 10^7}{12 \times 60 \times 44\,000} = 1{\cdot}4 \text{ kW}$$

The more hopeful type of solution is that in which a large estuary is dammed, the dam being fitted with sluice gates and containing turbines more or less as in a low-head river development. The reservoir so formed is filled at high tide and the water is retained behind the dam as the tide falls outside. When it has fallen so that sufficient difference of level has been established, water is allowed to flow out through the turbines in the dam, generating power. Alternatively, the method of working may be to lock the rising tide out while the reservoir remains empty, and the power is developed while water is allowed to flow in and fill the reservoir. Finally, if obvious practical difficulties can be overcome, it should be possible to combine the two and obtain power from the same turbines both on the inflow and on the outflow of the tide.

This power supply is intermittent, for, in order to obtain a working head, the reservoir cannot begin to empty until some time after it has been filled at high tide, and it must be quite empty before the tide rises again. Since the tidal period is 12 hours 25 minutes, the working periods become later each day and cannot be made to fit any load which occurs at the same hours each day. This problem is the one upon the solution of which the economical development of tidal power waits, namely, either to adapt or create industrial processes which will utilize power as and when it is available, or alternatively, to find a means of storing energy in order to fit the irregular supply to the variable demand of industrial load.

A further solution is to use an additional low-level tidal basin, or sump, into which water may be run either from the high tide or the high water in the main reservoir, at such times as power would not otherwise be available.

### Power from a Basin.

On a 20-ft. tidal range one square mile of reservoir area may be readily shown to represent energy equivalent to 132 000 kWh, i.e. it would lose this potential energy if it were discharged at low-water level. With the power developed on both inflow and outflow this would give a mean continuous output (at 100 per cent overall efficiency) of 22 000 kW per square mile.

The power available is proportional to the square of the tidal range. Some estuaries, e.g. the Severn, have neap tides of 20 feet and spring tides of 40 feet. The mean power is therefore at least double that given above for a range of 20 feet, and for 20 square miles of basin area would give (at 60 per cent overall efficiency) over 500 000 kW continuous power, or the equivalent of 1 000 000 kW peak capacity on an industrial load factor of 50 per cent. The Severn tidal-power scheme is of this order of magnitude, and at least as much power again is available around our coasts and is possibly on the margin of being commercially remunerative.

### Competition and Co-operation of Steam and Water-power Stations.

All other considerations apart, under a commercial system one absolute limit to the development of water power is the condition that it shall not be more commercially profitable to supply the same power at the same place by fuel-power stations. It is also true, however, that a combination of water and steam plants, electrically interconnected, is very often the cheapest way to meet a given power demand, even when abundant water power exists to meet it unaided. The economic solution depends upon the load factor of the load it is intended to supply, or upon the charges which energy at various load factors will bear. For example, a very high load factor may be obtained by developing electrochemical industries, but the cost per unit which will render this development remunerative is rigidly limited by the cost of alternative methods of production.

The costs of generating energy by any means may be divided into a cost specific to each unit and an overhead cost independent of the number of units generated, but depending mainly on the peak capacity. With a higher load factor the fixed charges are spread over a larger number of saleable units, and the cost per unit is decreased. If the fixed charges are large compared with the generating charges, a high load factor will have more effect in reducing the cost per unit than if the reverse is the case.

In hydro-electric installations there are many cases in which practically the whole costs are the fixed charges, i.e. interest on capital, rents, etc., and in such cases a high load factor is necessary if the cost per unit is to be small, and an installation which could not compete with steam at ordinary load factors might be a sound proposition if required to supply a specially high load factor.

In hydro-electric schemes involving expensive seasonal storage the reverse is the case. The amount of storage capacity required is fixed by the mean daily load, not the peak load, and hence the greater part of the reservoir cost is a cost proportional to the energy developed, i.e. to the load factor. In fact, the water has now a cost, just as fuel in a steam station has a cost, and the storage development is under exactly the same economic forces as a station using expensive fuel for every unit it develops. In this case the load factor of the station is of correspondingly small account, and it may be that such a station which could not compete with steam to supply continuous power could compete with it successfully under industrial load factors, though this would be an extreme case.

It will now be seen why a compound station may be the most economical proposition to meet a given load. It will be possible to keep part of the plant running constantly, part running, say, for 50 per cent of the time, part running for only the brief period of the peak loads, and part, the standby units, running only in cases of emergency. According to circumstances, water-power units will meet some of these demands best, and steam units will meet others best, and the station will be made compound.

In low-head developments without storage, i.e. where the water is either used or wasted, the steam units are therefore used to take the peak loads, and the water units are set to run constantly at their most efficient output, using all the water which is available up to their maximum capacity.

In high-head developments with seasonal storage it is sometimes better to run these steam stations at constant load and to take the peaks on the water, for the reason explained above.

Where high- and low-head developments are connected into a comprehensive system, as in Switzerland, it is the practice to run the low-head developments at constant power and take the peak loads from the storage stations.

In England, where there is considerable possibility of developing a large number of low-head stations of small power connected into the steam supply network, it would be possible to run these at continuous full load, and, though the load factor of the steam stations would be so much the worse, it is clear that this possibility renders the limit of cost per kilowatt which would make such a development possible, rather higher than it would otherwise be.

### Cost of Water-power Development.

There is a definite limit of capital cost which cannot be exceeded by a water-power development. This limit depends upon the distribution of the load through the day and upon the charge per unit which the prospective consuming process will bear, and cannot, therefore, be stated at a definite figure. It also depends upon the location of the water power.

It has been shown in the report of the Water Power Resources Committee that a liberal allowance for medium-sized plants for all the annual charges whatsoever is 11 per cent of the total initial outlay.

If the limiting expenditure for development is fixed solely by competition with coal-fired stations, the limiting cost per kilowatt may easily be estimated from the equation :—

11 per cent of this expenditure
= annual cost of the equivalent steam station.

On a pre-war basis a 5 000-kW steam-power station with coal at 10s. per ton, and with an annual load factor of 95 per cent, would cost about £37 000 per annum. This is 11 per cent of the allowable cost (pre-war) of a 5 000-kW water-power station, which makes its limiting cost per kilowatt £67 for the same duty. If the average value of money is, as at present, half its pre-war value, the present economic limit is twice as much, or £134 per kilowatt. At lower load factors the limit would be lower, probably about £45, i.e. the pre-war cost at 50 per cent load factor.

The cost per kilowatt of actual installations is very variable. A 10 000-h.p. station at Chedde in France cost only £7 per kilowatt. The average (pre-war) cost per kilowatt of the installations in various countries are as follows :—

| | £ |
|---|---|
| Canada (70 typical larger plants) .. | 17·7 |
| Canada and U.S.A (average) .. | 25·0 |
| Scotland .. .. .. .. | 33·0 |
| Sweden.. .. .. .. .. | 15·0 |

### BRITISH WATER-POWER RESOURCES.

The extent and availability of the water-power resources of the British Isles have just begun to attract the attention of engineers. The report of the Water Power Resources Committee of the Board of Trade has just been issued, and, although only selected districts were investigated by the Committee, they consider that in those districts there is power of 210 000 kW (continuous) in Great Britain capable of economic development and more than 200 000 kW (continuous) in Ireland. In Great Britain this represents 40 per cent of the total units generated for public supply, railways and tramways in 1917–18. In Ireland the amount is, of course, vastly more than the whole so generated. This leaves out much water power not investigated, particularly the low-head river sites in England. An investigation of a typical river, the Wiltshire Avon, showed 4·4 kW per square mile of catchment. The area of England is 50 000 square miles, and although this is very little data, it indicates that there are considerable resources not included in the Committee's estimate ; and there is also a total of at least 1 000 000 kW (continuous) of tidal power not far from the limit of economic availability.

### WATER-POWER DEVELOPMENTS ABROAD.

Almost every country has made rapid progress in the past 10 years in investigating and developing its water-power resources. Everywhere plans are made for huge developments which only await economic prosperity to be put in hand.

### GENERAL ECONOMIC EFFECTS.

The steady development of resources of this magnitude constitutes perhaps the most important engineering movement at present occurring. The causes for it are the technical advances in turbine and electrical engineering, the spread of the industrial point of view all over the world, and the effects of the war upon the supply of coal and of manufactured goods.

Probably about one-fifth of the total mechanical prime-mover power of the world is water power as at present in operation. It is certain that this fraction will be much increased in a few years' time. The available water power of the world is vastly greater than its power consumption, but its development will proceed slowly because it is very often situated away from industrial areas. It is certain, however, that in the long run the load will go to the power, and transport, which is one of the difficulties of development, will be provided where it is required.

This development has a double interest for this country. First, it is creating a demand for civil engineering plant electrical generating plant, high-tension transmission and control gear, industrial equipment, etc., which British engineers have to study. This demand can be met in the first place only by established industrial countries. It is also developing a market for trained industrial skill.

The ultimate effect of this movement towards universal industrial development, of which water-power development is one important aspect, may be less fortunate for the people of this country. We have held, together with a few other countries, a monopoly position as universal providers of manufactured goods. In so far as it does not depend upon new demands and increased consumption, the development of industry in new places must of necessity restrict the markets of the established countries. The process has not yet become important, but it seems probable that it will underlie the industrial history of the years when we shall be most interested in such movements.

# THE EFFECT OF LOCAL CONDITIONS ON RADIO DIRECTION-FINDING INSTALLATIONS.

By R. L. Smith-Rose, M.Sc., Associate Member, and R. H. Barfield, B.Sc., Student.

[Communicated by permission of the Radio Research Board.]

(*Paper first received 6th May, and in final form 27th September; read before the* Wireless Section *8th November,* 1922.)

## Summary.

This paper is an account of some of the experiments carried out during the past year by the Sub-Committee of the Radio Research Board on Wireless Direction Finding.

The majority of the work was done either at the Radio Research Station, Slough, or the National Physical Laboratory, Teddington.

The paper summarizes the work of previous investigators on the same lines, and indicates why further reasearch was necessary. It then describes experiments which provide quantitative data as regards the effect of metal work, coils, aerials, overhead wires and trees on a direction-finding set in their vicinity, and gives definite figures which show the extent in certain cases of errors produced by mountains and buildings.

## Introduction.

Modern direction-finding installations are well able to detect variations of less than 0·5° in the direction of arrival of the waves under observation. There are, however, many causes which may prevent the readings so obtained from corresponding to the absolute direction of the transmitting station observed to this degree of accuracy.

An analysis of the various classes of errors experienced in practice shows that by far the most important are those which have been somewhat vaguely termed "night effect," implying the variation in the apparent direction of arrival at the direction-finding station, a phenomenon which is observed with nearly all transmitting stations between sunset and sunrise. These variations commonly amount to 20° and have been observed by the authors to exceed 40° on certain occasions. Little is known, however, as to the cause producing these effects, though much has been surmised. No practical system has been put forward which avoids these errors, and there is, at present, little more to be said about them save that, by reason of their existence, radio direction-finding is practically restricted to the daytime except over very short distances.

Second in importance is the class of error dealt with in this paper, namely, the errors which are produced by the immediate surroundings of the installation.

Effects of this kind may be caused by neighbouring objects, or by local geographical conditions, and while the errors produced will be constant under ordinary circumstances and thus permit of correction of the bearings, in other cases it may be necessary to avoid all possible errors at the site of the installation. It was known previously that such objects as cliffs, hills and mountains, trees, masses of metal work, and overhead lines would produce very serious errors on a direction finder operated in the vicinity, while the special case of the effect of the metal hull of a ship has seriously engaged the attention of wireless engineers ever since the first ship was fitted with directional apparatus.

Round [*] has indicated these facts in a general way, while Ballantine,[†] in an account of some researches of the U.S. Navy Department, gives some interesting details of local errors met with in special cases. Hollingworth and Hoyle have also given the results of experiments conducted in this matter,[‡] while more recently Kolster and Dunmore have mentioned some of the errors experienced in towns and on board ship.[§]

Notwithstanding the above work, however, there is insufficient data on the matter indicating exactly what errors are produced, their probable magnitude and at what distance from the disturbing objects the receiver must be placed in order to render such errors negligibly small.

A knowledge of these facts is particularly important in selecting a suitable site for the erection of a directional radio installation. It is the experience of the authors that it is very difficult to obtain for direction finding an absolutely ideal site, which is not prohibitive for other reasons, particularly in the vicinity of towns. It has, for instance, been found desirable to have some idea as to which of several conditions will produce the least serious effect, and at approximately what spot the observed errors will be a minimum.

The experiments described in this paper were therefore carried out in order to obtain some quantitative knowledge of the disturbing effects of surrounding objects on a directional receiving set. Unless it is otherwise stated, the experiments were conducted with a direction finder of the Robinson or crossed-coil type,[‖] which was transported to and from the scene of operations as required. In a few cases, however, a smaller single-frame coil was used for convenience, and due mention will be made of this at the correct place. The orientation of the coil for each experiment was carefully carried out by means of a good prismatic compass, which could be relied upon to within ¼ degree.

---

[*] H. J. Round: "Direction and Position Finding," *Journal I.E.E.*, 1920, vol. 58, p. 224.

[†] S. Ballantine: "The Radio Compass," *Wireless Year Book*, 1921, p. 1131.

[‡] J. Hollingworth and B. Hoyle: "Local Errors in Radio Direction Finding," *Radio Review*, 1920, vol. 1, p. 644.

[§] F. A. Kolster and F. W. Dunmore: "The Radio Direction Finder and its application to Navigation," *Scientific Papers of the Bureau of Standards*, No. 428, 1922.

J. Robinson: "A Method of Direction Finding of Wireless Waves, and its Applications to Aerial and Marine Navigation," *Radio Review*, 1920, vol. 1, pp. 213 and 265.

The various obstacles and features of the surroundings which are dealt with from the point of view of their disturbing effect are classified as follows:—

(1) Metal work in small and large quantities above and below the ground.
(2) Overhead wires (e.g. telegraph and telephone wires or power lines).
(3) Tuned aerial systems and closed coils.
(4) Trees.
(5) Buildings.

### (1) METAL WORK IN SMALL AND LARGE QUANTITIES.

(*a*) *Small metal work.*—The presence of metal work near a receiving set would be expected to have some effect upon the working of the latter, owing to the currents induced in the metal by the arriving waves and to the inductive action of these currents on the receiving coil itself. Unless the metal work is arranged in the form of a closed loop near or around the circuit, the influence of such currents set up in stray metal work would not be felt at any appreciable distance from the metal object. It is easily shown experimentally that the presence of pieces of metal smaller than the dimensions of the coil system do not give rise to perceptible errors in the readings of the latter except when placed very close to the coil. It was found that various metal boxes used in connection with the screening of an auxiliary triode oscillator did not make any difference in the observed bearings when placed 5 or 6 ft. from the coil. Similarly, the screening box used for the amplifiers and batteries of the direction finder gives no noticeable errors when at a distance of 6 ft. from the centre of the coil system.

This latter box, which was constructed of sheet iron and the dimensions of which were 20 in. × 20 in. × 30 in., was found to produce an error in the bearing of Paris at Teddington of about 1·5° when placed at about 3 ft. from the coil's axis. The error was found to be greater when placed to one side of the coil perpendicular to the direction of Paris than when placed approximately in a line with Paris and behind the coil. By moving the box to the other side of the coil the apparent bearing was changed in the reverse direction. In these positions the box lies within 6 inches of the vertical sides of the large coil at certain settings, and the currents in the coil then probably induce other eddy currents in the metal, which will give additional effects in the former. By removing the metal box to a distance of 5 ft. the resulting error becomes inappreciable. When the box is placed inside the crossed-coil system the effect of the eddy currents is most marked, resulting in a large reduction of signal strength in the receiver.

The general conclusions thus arrived at are, therefore, that masses of metal work comparable in dimensions with the receiving coil do not perceptibly produce any errors in the bearings indicated by the latter except when placed within a very few feet of the coils. As a safe precaution it is as well to keep the space of, say, 10 ft. round the coil fairly clear of even small pieces of metal, as the cumulative effect of several small pieces may become quite appreciable. For this reason it is advisable to ensure that the hut or other structure containing the direction-finding set is as free as possible from metal in the way of joint-plates, door and window fastenings, etc., and that metal oil stoves or lamps are not placed too close to the receiving coils.

(*b*) *Long metal tube.*—When, however, the extent of the metal work in the neighbourhood is moderately great, the resulting errors in observed bearings become very much more serious. As an illustration of the order of the errors which may arise in such cases, the results of an investigation carried out on a large metallic tubular construction may be given. The "tube" was of approximately semi-circular cross-section, being formed of a number of curved, corrugated iron sheets bolted together and resting on flat, similar sheets placed on the ground. The tunnel so formed was 50 ft. long, and the height of the arch about 3 ft. 6 in.

The alteration, due to the tube, of the electromagnetic fields set up by waves arriving from various transmitting stations was then explored by means of a single receiving coil 2 ft. 6 in. square mounted on an axis in a horizontal base-board with scale and pointer. This coil, provided with tuning condensers and an amplifier and batteries, formed a very small, portable direction-finding set operating on the simple "minimum" principle, which could be used inside or outside the above tube. In each position in which the coil was used, the latter was set by means of a good prismatic compass to read either 90° or 270° when the plane of the coil was in the geographical meridian. When the coil was then turned to the minimum position for any received signals, the pointer indicated directly the bearing of the station observed. This setting of the coil could be made to about 0·25°, and a few check-experiments carried out with the coil set up in an open field well away from all obstacles showed that it gave correct bearings, as indicated by the "standard" direction-finding set in use at the station. This latter set was used as a frequent check throughout the experiments, to ascertain the changes produced by the alteration in position of the smaller coil. The average accuracy of

TABLE 1.

*Relation between the Change in Apparent Bearing produced at the Centre of the Tube, and the True Direction of the Waves relative to the Tube's Axis.*

| Transmitting station | Directions relative to axis of tube | Change in apparent bearing |
|---|---|---|
| | degrees | degrees |
| Nauen .. .. .. | 2 | 12 |
| Budapest .. .. .. | 27 | 32 |
| Paris .. .. .. | 69 | 14 |
| Aranjuez .. .. .. | 115 | 16 |
| Horsea .. .. .. | 131 | 26 |
| Poldhu .. .. .. | 169 | 14 |
| Cleethorpes .. .. | 292 | 15 |
| Karlsborg .. .. | 323 | 29 |
| Moscow .. .. .. | 348 | 16 |

the readings obtained on the latter was about 0·5°, which was considered quite sufficient for the purpose required.

The influence of the metal tube first became appreciable when the coil receiver was placed about 30 ft. from either end of the tube and on its axis, when an error of bearing of about 1° was produced. When placed at the open end of the tube, this error increased to 2°–5° for various transmitting stations. As the coil was then moved down the axis inside the tube, the error increased rapidly to a maximum value over a distance of about 15 ft. on either side of the centre of the tube, this maximum error varying with the direction of the arriving waves relative to the tube's axis and becoming as great as 29° in one case. Table 1 summarizes the mean values of several readings taken on the different transmitting stations, and also shows the directions of these relative to the tube.

In each case the change in the apparent bearing was towards the normal to the tube's axis, showing that the magnetic field resulting from the incoming waves is deflected in a direction towards the axis of the tube. Table 1 shows that the deflection produced is of the nature of a quadrantal error. Immediately the coil was placed inside the tube a very marked decrease in signal strength was observed, which is evidently due to the eddy-current losses resulting from the currents set up in the metal work by the incoming waves. The greatly increased effect of metal work when placed in the form of a partly or completely closed loop is well demonstrated by the above results, and illustrates the effect which might be expected if, for example, a directional wireless receiver were installed in a corrugated-iron building. The continuity of the metal structure would appear to be very important, and even with such large masses the nearest portions of these have by far the greatest effects. For example, with the above coil receiver placed inside the tube near the centre, the removal of a section of the tube, 2 ft. 6 in. long, forming the top sides reduced the error in the apparent bearing of Paris from 14° to 1°. Similarly, by unbolting two adjacent sections and slightly separating them, a change of 2° or 3° was produced.

With the receiving coil set up along the outsides of the tube, the errors observed were very much less than those recorded above, ranging from 5° to 9° at a distance of 2 ft., to about 2° at 3 ft. from the side of the tube. Also, when the coil was placed on top of the tube the errors varied from 2° to 6°.

(*c*) *The case of a ship.*—As a further example of the effect of large masses of metal work upon the readings of a directional receiver, the effect of the metal hull of a ship may be instanced. In June 1921 one of the authors installed a standard Robinson direction-finding set on one of H.M. surveying ships, with the kind permission of the Hydrographer to the Admiralty, who has shown great interest in the experiments. The particular ship chosen is normally working in the North Sea some 30 to 50 miles out from the coast. The set was installed on the upper deck of the ship and the frame was set as accurately as possible on the centre line, with the scale of the coil reading 0° to 180°. Any observed reading on the direction-finding set was thus made relative to the head of the ship. The direction of the ship was obtained from the standard compass and, after correcting for compass error and magnetic variation, the apparent wireless bearing of the distant transmitting stations could be obtained. A large number of observations on various transmitting stations were taken in this manner.

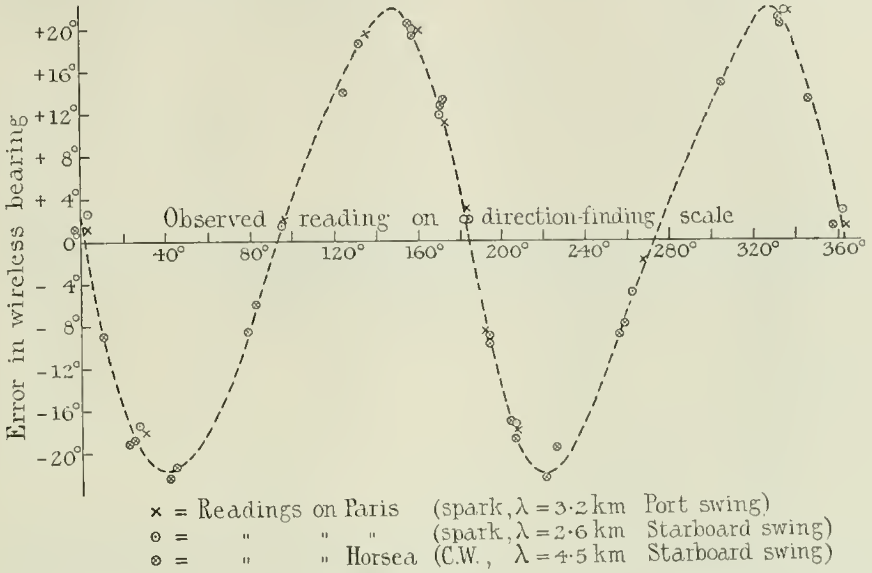


FIG. 1 (*a*).—Observations of bearings made on H.M.S. "Fitzroy" during swinging of ship, 17th October, 1921.

The earlier experiments soon showed that the metal work of the ship had a considerable effect on the observed readings of the direction finder. It was therefore arranged to "calibrate" the ship by gradually swinging to various points of the compass, and taking sets of observed bearings on the same transmitting station.

The stations observed during the successive swings were Paris (3·2 km wave), Paris (2·6 km wave), and Horsea (4·5 km wave), and the results are shown in Fig. 1 (*a*) plotted in the form of error of bearing against reading on the direction finder. In Fig. 1 (*b*) the same results have been plotted to show the deviations against the actual direction of the incoming waves relative to the ship.

In consideration of the conditions under which the observations were made, the results are seen to lie fairly accurately on the mean curves plotted, and the latter demonstrates well the following points:—

(i) That when the arriving waves come from either approximately fore and aft or athwartships, the error in the reading is reduced to zero.

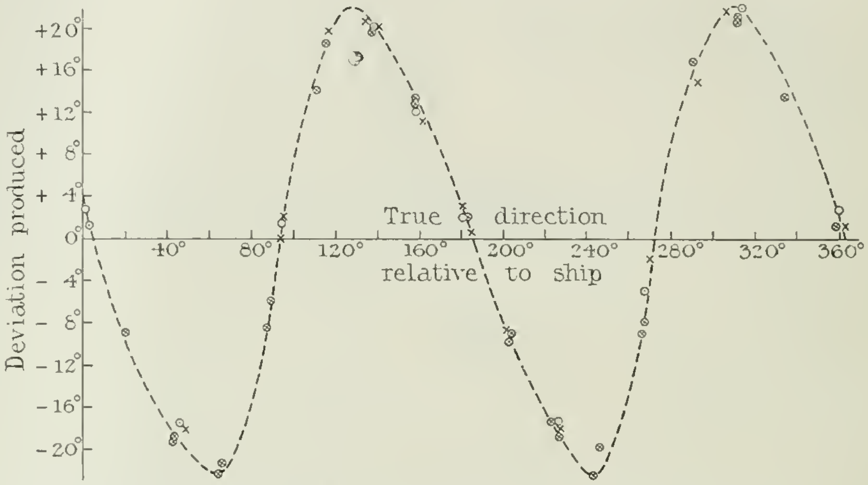


FIG. 1 (*b*).—Observations of bearings made on H.M.S. "Fitzroy" during swinging of ship, 17th October, 1921; plotted to show the deviation produced on waves arriving at various angles to the ship.

(ii) That in intermediate directions the results are in error by amounts varying up to 22° in either direction.

(iii) That there is a tendency for the readings to be concentrated along the fore-and-aft line of the ship.

(iv) That there is no appreciable difference in the error incurred on the different wave-lengths used, viz. 2·6, 3·2 and 4·5 km.

Conclusions (i), (ii) and (iii) above are in direct accordance with the experience of previous investigators. Further experiments on other transmitting stations have confirmed conclusion (iv) over the range of 2·6 to 6·0 km.

The theoretical treatment of the deviations of electromagnetic waves due to a metal cylinder half immersed in sea water has been given by R. Mesny,* who shows that the deviation curve for such a case should be sinusoidal. The departure of the curve in Fig. 1 (*b*) from sine-wave form may easily be due to the departure of the general shape of a ship from the above ideal form.

It would be expected from these theoretical considerations that a directional receiving set mounted symmetrically over a metal ship would have a zero error for readings of 0°, 90°, 180°, etc., whereas the above curve is displaced some 5° or 6° from these positions. As the setting of the coil on the ship was considered to be correct to within 1°, this difference may be due to some asymmetry in the distribution of the metal work on the ship, particularly on the deck.

The above results show, therefore, that when the mass of metal work is very large compared with the receiving coils, as in the case of a ship, the resulting errors in the observed bearings on the direction finder may be very serious; although, when the set is fixed in position on the ship, the necessary correction may be made from such a curve as that given in Fig. 1 (*a*).

(*d*) *Underground metal work.*—The effect of masses of metal work in producing large errors in the reading of a radio direction finder may in some instances be utilized for the location of such metal work, when the latter is not visible or when its presence is not readily detected by other means. An interesting example of this was recently obtained at the Aberdeen University direction-finding station of the Radio Research Board. This station was erected on a site which appeared to be fairly good as far as conditions above ground-level were concerned, but when it was operated some large errors were soon found in the apparent directions of the incoming waves. These errors were found to be practically permanent in the daytime, and Fig. 1 (*c*) shows graphically the mean day errors experienced in the daytime between June 1921 and April 1922. From a comparison of this and the previous curves it will readily be seen that one possible cause of such a curve of errors would be the existence of a mass of metal work the greater axis of which is in the direction 163°

---

* R. MESNY: "The Diffraction of the Field by a Cylinder, and its Effect on Directive Reception on Board a Ship," *Radio Review*, 1920, vol. 1, pp. 532 and 591.

from true North, and passing directly beneath the direction finder.

By means of a portable directional receiving set the authors explored the site and found that the errors were closely associated with a line of manholes indicating the location of a sewer crossing the adjacent fields at an angle of 170° from true North. The hut containing the standard direction-finding set was inadvertently erected almost directly above this sewer at a point where the latter rose to within 18 in. of the surface. The sewer was of ordinary brick and concrete construction and contained no metal work except at the manholes, and it seemed unlikely that this could be responsible for the effects observed. An inspection of the necessary plans, however, showed that the part of the sewer in the immediate locality of the direction-finding hut was a section of special construction, owing to its proximity to the surface, was supported by a strip of expanded steel 6 ft. wide and 300 ft. long, and was 8 ft. below the surface at the hut. In addition to this, the sewer crossed a small stream at a point about 14 ft. from the hut, and the stream was conducted under the sewer by means of an iron pipe about 40 ft. long. The existence of this metal work entirely beneath the surface may therefore be considered to have been predicted from the readings obtained on the radio direction finder. It is to be expected that other large masses of buried metal work, such as gas and water mains, will have a similar effect in their vicinity.

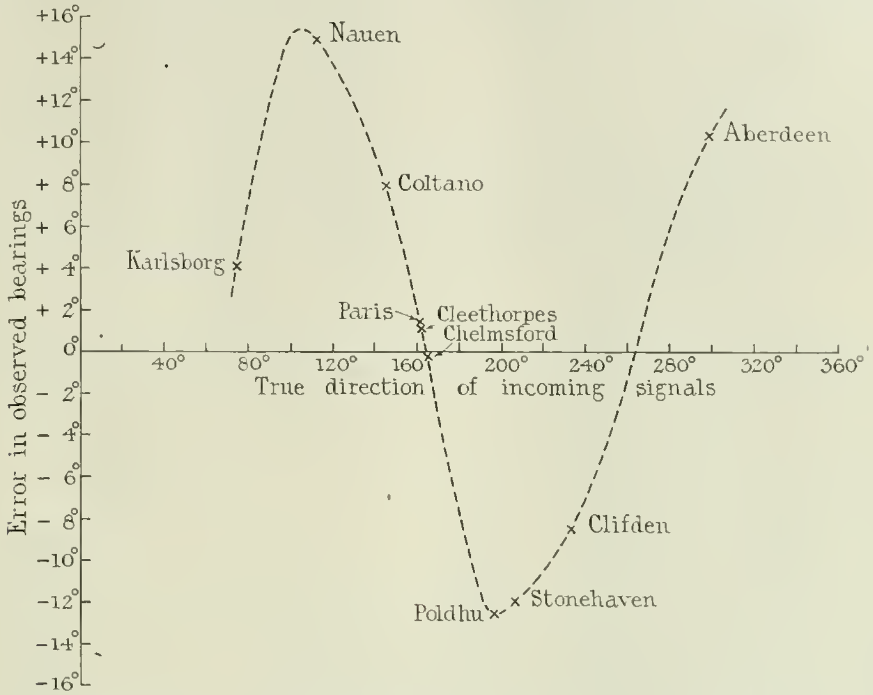


Fig. 1 (*c*).—Curve showing permanent deviations in bearings at Aberdeen University direction-finding station. Mean day error observed from June 1921 to April 1922.

### (2) Overhead Wires.

A possible cause of errors which is frequently encountered in selecting a site for a direction-finding set, is the presence of overhead conducting wires. From the conclusions arrived at in Section (1), it might be considered that a bunch of such wires, being of comparatively small bulk, would produce only small errors, and these only at distances of a very few feet from the wires. The experiments about to be described, however, show that when the wires extend for a considerable distance the effects produced in their neighbourhood can be very large indeed.

It should here be emphasized that, in any attempt to study the effect of a local condition on a directional radio installation, every precaution must be taken that other conditions are either ineffective or else remain constant throughout the experiments. The fulfilment of this provision was found to be somewhat difficult in the present case, where a convenient situation of overhead telegraph wires was required quite free from hills, trees, wire fences, etc., which might produce other effects quite extraneous to those sought after.

One fairly satisfactory site was, however, found near the Slough station, and a number of experiments were carried out with the small frame coil mentioned in Section (1) in connection with the metal tube experiments. The site selected was on the main Bath-road about 1 mile east of Slough, along which are installed a large number of overhead trunk telephone wires connecting London with the West of England. About 40 wires were carried on poles along each side of the road, the lowest wires being about 20 ft. above the road. With the exception of a hedge along either side of the road, the surrounding land was quite free from obstacles, and a point was chosen at which a track led off to the South, approximately at right-angles to the road, and along which the experiments could be carried out.

The frame coil was first set up immediately underneath the wires along the south side of the road and correctly oriented in the geographical meridian. Readings of the apparent bearings of various transmitting stations were then taken in the usual manner. It was at once noticed that the readings obtained were considerably different from the correct values, and it was also noticed that the bearings changed considerably from time to time during the tests. For example, the apparent bearing of Paris, after remaining in the region of 90° for about 10 minutes, suddenly changed to about 65°, returning a few minutes afterwards to 85°, the true bearing of Paris being 143·9°. These effects were confirmed by similar tests made several days afterwards, when the bearings reached as low as 45°. Similarly, Chelmsford's bearing during the experiments varied from 35° to 42°. A possible cause of these rapid changes is the alteration of circuit conditions on the telephone wires at the various exchanges to which they are connected.

TABLE 2.

*Change in Apparent Bearings due to Two Sets of Overhead Wires* (38 *and* 46 *in number*), *laid in the Direction* 127·5° *from True North.*

| Distance from plane of wires | Station observed | Wave-length | Mean observed bearing | True bearing | Error due to wires |
|---|---|---|---|---|---|
| ft. | | km | degrees | degrees | degrees |
| 0 | Paris | 2·6 | (1) 272·3 | 143·9 | + 128·4 |
| | | | 92·3 | | − 51·6 |
| 0 | Paris | 2·6 | (2) 249·0 | 143·9 | + 105·1 |
| | | | 69·0 | | − 74·9 |
| 30 | Paris | 2·6 | 159·3 | 143·9 | + 15·4 |
| 60 | Paris | 2·6 | 150·8 | 143·9 | + 6·9 |
| 90 | Paris | 2·6 | 147·8 | 143·9 | + 3·9 |
| 120 | Paris | 2·6 | 146·3 | 143.9 | + 2·4 |
| 0 | Paris | 3·2 | 171·6 | 143·9 | + 27·7 |
| 90 | Paris | 3·2 | 145·9 | 143·9 | + 2·0 |
| 120 | Paris | 3·2 | 145·5 | 143·9 | + 1·4 |
| 0 | Nauen | 3·9 | 85·5 | 77·7 | − 12·2 |
| 90 | Nauen | 3·9 | 74·8 | 77·7 | − 2·9 |
| 120 | Nauen | 3·9 | 73·5 | 77·7 | − 4·2 |
| 0 | Chelmsford | 3·8 | (1) 41·0 | 70·9 | − 29·9 |
| 0 | Chelmsford | 3·8 | (2) 35·0 | 70·9 | − 35·9 |
| 60 | Chelmsford | 3·8 | 63·5 | 70·9 | − 6·0 |
| 120 | Chelmsford | 3·8 | 65·0 | 70·9 | − 5·9 |
| 0 | Coltano | 4·2 | 115·0 | 132·5 | − 17·5 |

Having observed the effect of the wires immediately beneath them, the receiving set was then moved away from the road in steps of 30 ft., and the apparent bearings of the various stations were taken at each stage. A summary of the results obtained is given in Table 2, each observed bearing being the mean of several readings taken during the experiments. All readings were taken in duplicate, with the coil in the normal and reverse positions to compensate for any antenna effect in the system which was, however, only of the order of 1°. The readings denoted by (1) and (2) were taken on different days in the same position.

These results show that errors ranging from 12° to 70° may be produced on a direction-finding coil mounted immediately underneath telephone wires some 20 ft. high. The errors produced diminish rapidly as the coil is moved away from the wires, but, even at the distance of 120 ft. from the line of wires, the errors may be a few degrees. At this distance of 120 ft. the effect of the wires on the bearings of Paris was practically negligible, as the error of 1·4° recorded above is exactly the same as that experienced on the standard set at the Slough station, about 1 mile away from the site of the present experiments. As the latter set is mounted in what is considered a nearly "ideal" site, this error must be due to some extraneous cause. The increase in the error on Nauen, when the coil is moved from 90 ft. to 120 ft. from the wires, also suggests the operation of some cause other than overhead wires; possibly the neighbouring trees, although there were only one or two of these within a radius of 100 yards or so.

The explanation of the above effects must remain very obscure, since it is impossible to realize the conformation of the circuits of the telephone lines at any particular instant. In one sense the overhead wires may be pictured as constituting the top side of a huge vertical frame, of which the earth forms the lower side, and the vertical sides are formed by the connections to earth at the various exchanges. An electromagnetic wave arriving at an angle to the plane of this large frame would suffer a partial absorption of that component of its magnetic field perpendicular to this plane, and the resultant field would therefore affect a direction-finder coil by giving an apparent direction deflected towards the normal to the plane of the wires. In Table 3 the results obtained immediately underneath the wires are collected, and the true direction of the station is given relative to the wires.

TABLE 3.

*Change in Apparent Bearings immediately beneath the Wires.*

| Station observed | True bearing of station relative to wires | Deviation of observed bearing |
|---|---|---|
| | degrees | degrees |
| Coltano . . . . . . | 5·0 | − 17·5 |
| Paris (2·6 km) . . . . | 16·4 | − 51·6 |
| Paris (3·2 km) . . . . | 16·4 | + 27·7 |
| Chelmsford . . . . . . | 303·4 | − 29·9 |
| Nauen . . . . . . | 310·2 | − 12·2 |

Shown in this manner it is seen that, in the case of Paris (3·2 km), Chelmsford and Nauen, the apparent direction is deflected towards the normal to the plane of the wires. Paris, on the 2·6 km wave, showed some freak effects in the experiments and was evidently subject to some other influence, possibly a resonance condition in the overhead line circuits. At points away from the wires, as shown in Table 3, it exhibits effects similar to those obtained with the 3·2 km wave, and is thus in accordance with the above reasoning. The waves from Coltano arrive nearly along the direction of the wires, and are apparently deflected in the wrong direction. It should be remembered, however, that the overhead wires are not straight over any appreciable portion of their route, and, in fact, suffer a large deviation within $\frac{1}{4}$ mile on both sides of the site of the experiments described. The "effective" plane of the wires may therefore be several degrees different from their direction at any particular point, and this may easily account for such discrepancies as that presented by Coltano.

Some later experiments were carried out under a line of 12 wires, branching off the above main route, at about the centre of their run of less than $\frac{1}{2}$ mile. In this case deviations of bearings ranging from 8° to 31·4° on a few stations were observed underneath the wires, these errors decreasing to from 1° to 6·4° at a point 60 ft. away. It would thus appear that the errors produced are not directly influenced by the actual number of wires near the site, but depend on the conditions of a whole circuit of wires, which may extend over several miles.

It is thus seen that the presence of overhead metal wires in the neighbourhood of a directional wireless receiver may produce very serious errors on the latter, even at a distance of 100 or 200 ft.

### (3) TUNED AERIAL SYSTEMS AND CLOSED COILS.

A comparatively short overhead wire system such as that of an ordinary "open" radio-telegraphic aerial would naturally be considered to have a much greater influence on the readings of a direction finder when it is tuned to the incoming waves. In this case the possibility of an additional field due to re-radiation or induction from the aerial is not remote. A. H. Taylor drew attention to this possibility in some experiments which showed that the tuning-in of a neighbouring aerial some 20 ft. away produced no effect on the direction-finder coils unless the aerial lead was brought to within 8 inches of the latter, when a change of 3·8° in the apparent bearing was produced.*

An instance of a much greater effect than this is also quoted by Hollingworth and Hoyle,† in which the tuning-in of an aerial $\frac{1}{4}$ mile away produced an error of about 4°, but only when the aerial was almost exactly on the line joining the transmitter and the direction finder.

At the spot chosen for the erection of the direction-finding set at the National Physical Laboratory, two single-wire aerials were originally suspended from a mast some 300 ft. away from the set (see Fig. 2). The nearer of these aerials, however, passed within about 40 ft. of the coils at the nearest point of its length of 350 ft. One of the aerials was constantly tuned to the short wave-length of Paris (2·6 km) for the reception of time signals, while the other and nearer aerial was usually directly connected to earth. It was shown by the daily observations made on the direction-finding set that the mere existence of these aerials, proved by their subsequent removal, made no appreciable difference in the observed bearings.

Before their removal, however, the opportunity was taken of making a few experiments on the effect of tuning the aerials. The experiments were made by setting one observer to take readings of the apparent bearing of the transmitting station at regular intervals of 1 minute, while the aerial was alternately tuned to the incoming waves and then connected to earth at intervals without the knowledge of the above observer. In this manner a number of readings taken with the aerial tuned were interspersed with the readings taken with the aerial earthed. Observations were made in this manner for several successive days, and, by taking the mean of each set of readings, a fairly reliable average bearing was obtained for each condition of the aerial, independent of any small day variations. The results obtained are shown in Table 4.

TABLE 4.

*Effect on Observed Bearings of Tuning a Neighbouring Aerial.*

| Station observed | Wave-length | With aerial earthed | | With aerial tuned | | Difference due to tuning aerial |
|---|---|---|---|---|---|---|
| | | No. of obsvns. | Mean bearing | No. of obsvns. | Mean bearing | |
| | km | | degrees | | degrees | degree |
| Paris .. | 2·6 | 8 | 144·6 | 8 | 144·5 | − 0·1 |
| Paris .. | 3·2 | 26 | 145·0 | 27 | 144·9 | − 0·1 |
| Horsea | 4·5 | 32 | 218·4 | 28 | 217·8 | − 0·6 |

In the case of the observations on Paris both the above-mentioned aerials were adjusted, as it was observed that the effect with one was very small. It is seen from Table 4, however, that the total effect of both aerials is only to produce a change in bearing of about 0·1°, and this result is consistent for both the wave-lengths used by Paris, although the actual bearings on these two wave-lengths differ owing to other causes. For the Horsea observations, however, only the nearer aerial could be brought into resonance, and this operation is seen to produce a change of 0·6° in the apparent bearing. This increased effect may have been due to the fact of the latter waves being continuous, as distinct from the damped waves used in the Paris transmission, and the effect also probably depends upon the relative directions of the aerial and the incoming waves.

A new and much larger multi-wire aerial just erected at the National Physical Laboratory has been found to produce an alteration in the bearing of Paris of 4 to 5°, when tuned to the same wave-length, although the nearest point of the aerial is over 120 ft. from the direction finder, and the leading-in wire of the aerial, where the current will naturally be a maximum, is about 300 ft. away. Further experiments will be carried out on this effect.

---

* A. HOYT TAYLOR: "Variation in Direction of Propagation of Long Electromagnetic Waves," *Scientific Papers of the Bureau of Standards*, No. 353, 1919.

† See footnote on page 179.

The proximity of a closed coil may affect the readings of a direction finder in a manner similar to a tuned aerial system. This question arose from the necessity of using two of the Robinson sets at Teddington in the same hut, about 80 ft. apart. Several sets of simultaneous obervations taken on these two sets, however, failed to show any consistent error at either due to the presence of the other. Some further experiments were later carried out on the effect of a large single-frame coil, 5 ft. square, placed at various distances from the standard direction-finder set. In each position the effect was tried of short-circuiting the coil and of tuning it to the incoming waves, while observations were made on the Robinson set. With a distance of 35 ft. between the coils the effect of tuning produced an error in the mean bearings of only 0·1°. When the distance was reduced to 18 ft. the effect was variable for different stations but was never greater than 0·5°.

When the single coil was brought up to within 10 ft. of the direction finder, the error produced in the bearings on the latter ranged from 1° to 2° on Paris, and from 0·5° to 1·8° on Nauen. The bearing was changed immediately the coil was tuned, there being no apparent error due merely to the presence of the coil, when this was either on open circuit or short-circuit. The bearings on the direction finder might, however, be appreciably affected by the presence of an open coil when working near the natural wave-length of the latter. The possibility of this was well demonstrated in one case where a partly-wound frame stood some 6 or 8 ft. from a direction finder and produced an error of nearly 4° on the readings of the latter on certain wave-lengths. The error disappeared when the frame was removed to a distance of 30 ft.

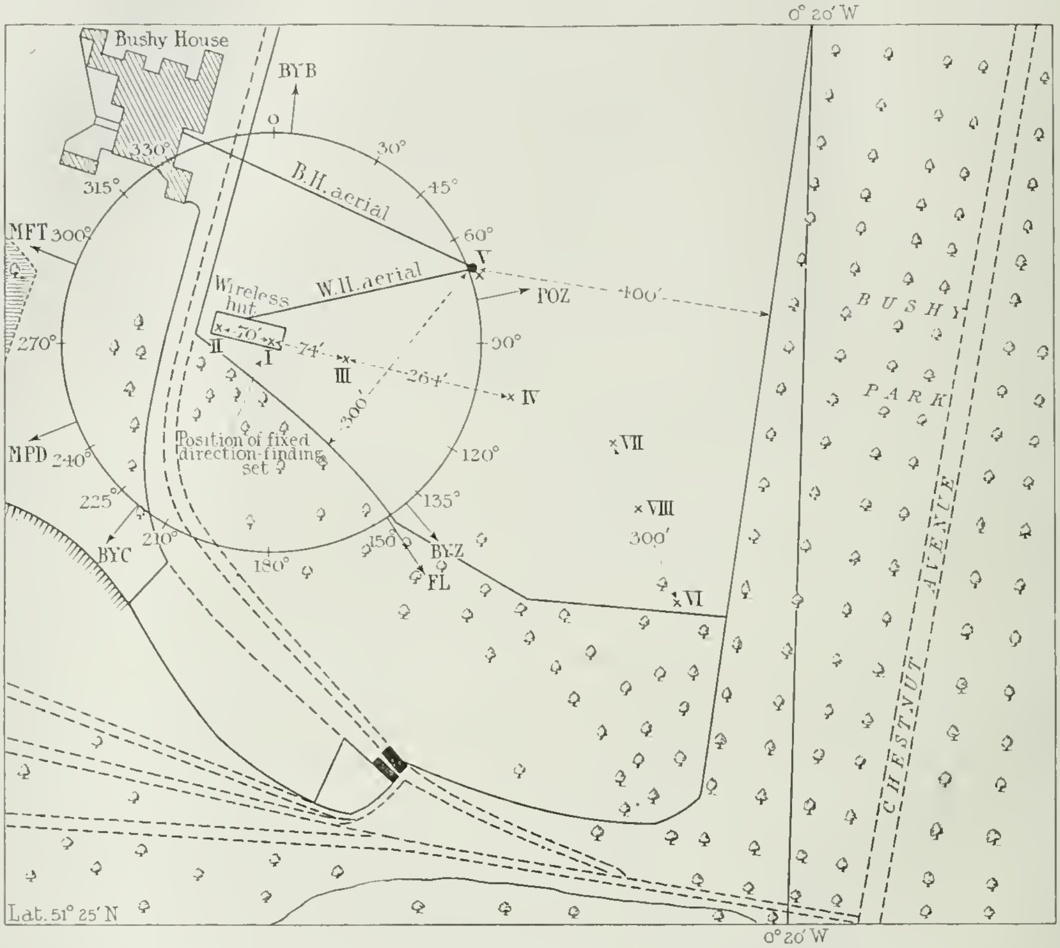


FIG. 2.—Plan of neighbourhood of wireless hut at the National Physical Laboratory, Teddington, showing aerials and positions explored in finding the effect of trees.

It was not considered profitable to carry out further experiments on the effect of tuned coils in the neighbourhood, for instance, the variation in the error with the change in orientation of the coil relative to the direction-finding set, etc. The results were sufficient to justify the practice in accurate working of keeping all frame coils at least 100 ft. from a directional receiving set, especially if both sets of coils are in operation simultaneously.

### (4) Trees.

It has been known for some considerable time that the presence of trees has a considerable effect on the propagation of electromagnetic waves. Duddell and Taylor in some experiments * carried out in Bushy Park in 1905 showed that the presence of clumps of trees between a radio-telegraphic transmitter and the receiver considerably decreased the signal strength at the latter.

More recently also Squier † has shown that growing trees can be used very effectively as aerials for the reception of signals over long or short distances.

A large tree may thus reasonably be regarded as being equivalent to a vertical aerial in which oscillatory currents are induced by the arriving electromagnetic waves, and these currents may give rise to secondary effects due to induction or re-radiation. Since, however, the tree will possess a fairly high resistance, and it is naturally an untuned circuit for most wave-lengths, the presence of single, isolated trees would not be expected to have much effect on a direction-finder coil unless placed in very close proximity to the trees. With large masses or clumps of trees, however, a cumulative effect may be produced in regard to the secondary field, which may give rise to serious errors at a directional receiving installation.

Table 5.

| Station | Paris (2·6 km) | | Poldhu (2·8 km) | | Paris (3·2 km) | | Nauen (3·9 km) | |
|---|---|---|---|---|---|---|---|---|
| Position of set No. 2 | Mean observed bearing | Departure of observed from true bearing | Mean observed bearing | Departure of observed from true bearing | Mean observed bearing | Departure of observed from true bearing | Mean observed bearing | Departure of observed from true bearing |
| | degrees | degrees | degrees | degrees | degrees | degrees | degrees | degrees |
| II* | 144·7 | − 1·0 | 249·0 | + 1·3 | 145·0 | − 0·6 | 76·7 | + 0·3 |
| III* | 146·7 | + 1·1 | 249·7 | + 2·0 | 146·1 | + 0·5 | 78·4 | + 2·0 |
| IV* | 147·9 | + 2·3 | 250·1 | + 2·4 | 147·2 | + 1·6 | 78·1 | + 1·7 |
| V* | 147·0 | + 1·4 | 247·1 | − 0·6 | 146·3 | + 0·7 | 76·2 | − 0·2 |
| VII* | 146·9 | + 1·3 | 250·2 | + 2·5 | 146·0 | + 0·4 | 78·5 | + 2·1 |
| VI* | 141·7 | − 3·9 | 250·2 | + 4·5 | 141·5 | − 4·1 | 78·2 | + 1·8 |

* The figures refer to the positions in Fig. 2.

Experiments were therefore carried out in the grounds of the National Physical Laboratory to obtain some knowledge of the magnitude of the effect of neighbouring trees on a direction finder. A plan view of the scene of these experiments is shown in Fig. 2. The position of the standard direction-finding set at Teddington is indicated by the point I in one corner of a large, open field bounded on the south and east by large masses of trees, and on the north and west by residential buildings and the Laboratory buildings, respectively. The nearest building is some 200 ft. from the receiving set, and the remaining buildings are at more than 3 times this distance. There are no overhead wires in the neighbourhood, and the effect of the aerials has been dealt with in the previous section. As, however, the nearest trees are within 40 ft. of the receiver it was thought that these might account for some of the permanent errors experienced at Teddington.

While maintaining set No. 1 fixed in position and taking frequent check-bearings therewith, a second set No. 2 was placed successively in the various positions indicated by II, III, IV, etc., in Fig. 2, and bearings were taken on two or three well-known fixed stations. In the first series of experiments the changes in position were fairly large, as indicated in the figure. A summary of the results of the bearings observed in each position is given in Table 5. Check-bearings were taken simultaneously on set No. 1 in a fixed position, and these showed a variation during the experiments ranging from 0·1° to 0·4°. The mean variation during each experiment was applied as a correction to the mean observed bearing on set No. 2 in each position, and this mean bearing was then corrected for scale errors. The tabulated readings are, therefore, made independent of scale error and any change of external conditions. The setting of the coil was made in each case by the prismatic compass, and is probably reliable to about 0·2°.

These results show very clearly the effect of the proximity of the trees. The general trend is for the error in the apparent bearing to be progressive for positions II, III, IV, VII, and VI, i.e. as the direction-finder set is taken into the junction of the large masses of trees to the east and south of the field. On the whole the error is a minimum in position V, which is the point farthest from all the trees, being in fact about 300 ft. from the nearest tree. The difference in the apparent bearing at positions V and VI is seen to be over 5° for Paris and Poldhu, and 2° for Nauen. The errors on the latter station are consistently smaller than on the others, probably due to the fact that the waves from Nauen (POZ) come across the open field to the receiver, while those from Paris (FL) and Poldhu (MPD) come directly through the trees, as indicated in Fig. 2.

---

* W. Duddell and J. E. Taylor: "Wireless Telegraphy Measurements," *Journal I.E.E.*, 1905, vol. 35, p. 321.

† G. O. Squier: "Tree Telephony and Telegraphy," *Journal of the Franklin Institute*, 1919, vol. 187, p. 657; also *Electrician*, 1920, vol. 84, pp. 111 and 147.

Owing to the varied distribution of the trees, it is somewhat difficult to draw any conclusions more definite than the above. For example, the change in sign of the error on Paris in positions II and III, and VII and VI is probably due to the actual path of the waves through the trees. The bearing on the long wave of Paris is seen to be consistently lower than that on the short wave, although it varies somewhat for the different positions. It is possibly partly due to instrumental error, or to some other influence more remote from the receiver.

The increase in the error obtained when the direction finder is taken much closer to the trees was well demonstrated by the second series of experiments, which were confined to observations made on Paris and carried out between positions VI and VII on a line approximately in the direction of Paris, as shown in Fig. 3. These positions are all within about 300 ft. of the trees, and the results obtained (duly corrected as above) are given in Table 6.

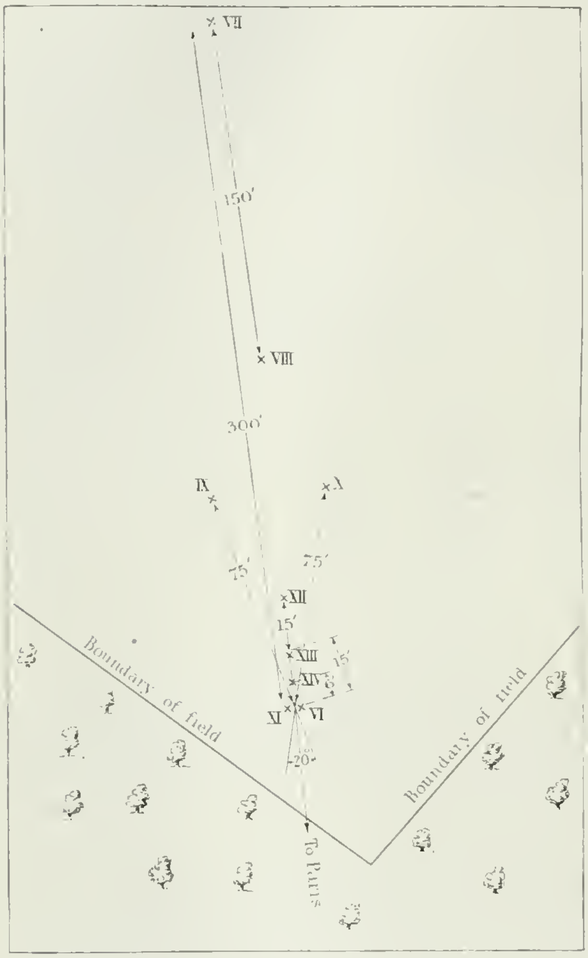


FIG. 3.—Investigation of the change in the observed bearing of Paris (FL) in the neighbourhood of position VI (see Fig. 2).

The most noticeable point about these latter results is the extent to which the bearing may change for a very slight change in the position of the receiving set. Thus, at positions X and XI (only 75 ft. apart) the difference in the observed bearings is 9·1°. These large changes are probably due to the difference in phase effects of the inductive fields from the different trees. The two sets of experiments thus demonstrate quite well that the presence of trees within about 300 ft. from a direction-finding installation may produce quite large, measurable errors in the readings of the latter. As it is possible that the error may vary with the changing state of the trees at the different seasons, the error may be a variable one and hence is to be avoided if possible.

TABLE 6.

*Observations made on Paris Signals in the Neighbourhood of Trees.*

| Position of Set No. 2 | Mean observed bearing | Difference of observed from true bearing |
|---|---|---|
| | degrees | degrees |
| VII | 146·9 | + 1·3 |
| VIII | 146·6 | + 1·0 |
| IX | 147·6 | + 2·0 |
| X | 148·1 | + 2·2 |
| XII | 146·9 | + 1·3 |
| XIII | 146·7 | + 1·1 |
| XIV | 144·6 | − 1·0 |
| XI | 138·7 | − 6·9 |
| VI | 141·9 | − 3·7 |

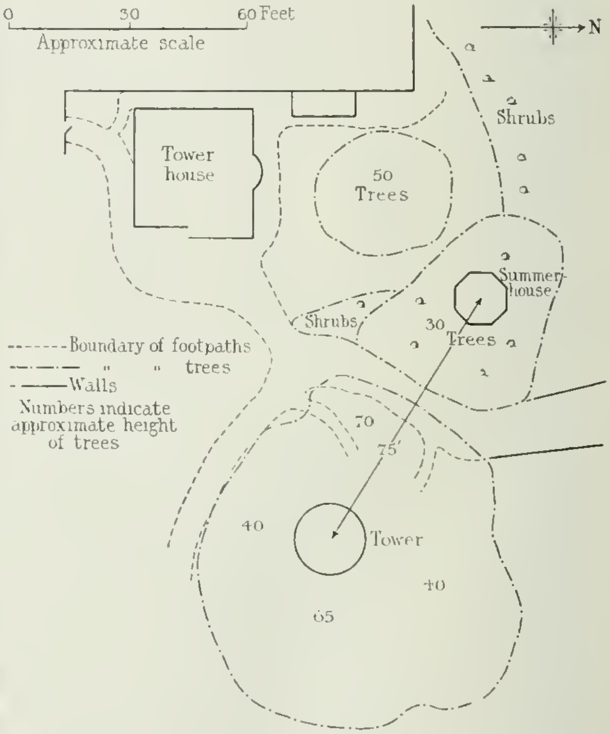


FIG 4.—Site of experiments on trees at Bristol University.

*Further observations upon the effect of trees.*—At the request of one of the authors, Mr. M. G. Bennett, B.Sc., the observer at the Radio Research Board Direction-Finding Station at Bristol University, has carried out some experiments on the effect of trees on wireless bearings. The standard directional receiver at Bristol is erected on the top floor of a stone tower, about 60 ft. above the ground. The tower is practically surrounded by trees within a radius of 60 to 100 ft., and those in the immediate neighbourhood of the tower were pruned to a height less than that of the receiver. All metal work was removed from the tower previous to the erection of the set.

A plan of the tower and its surroundings is shown in Fig. 4. In addition to this set, a small single-frame coil receiver was used for observation of bearings in two positions on the ground: (1) at the base of the tower, and (2) in the wooden summer-house (shown in Fig. 4) about 75 ft. away from the tower. The orientation of these coils was carried out by means of a theodolite and is correct to within 0·25°.

Observations were made on several transmitting stations for two or three days in each position, and a summary of these results is given in Table 7. All the results obtained are correct to about 1°.

TABLE 7.

*Effect of Trees on Observed Bearings at Bristol.*

| Station observed | Wave-length | True bearing | Observed bearings | | | Max. change in observed bearing |
|---|---|---|---|---|---|---|
| | | | At top of tower | At base of tower | In summer-house | |
| | km | degrees | degrees | degrees | degrees | degrees |
| Paris .. | 2·6 | 127·8 | 127·6 | 127·3 | 128·7 | 1·4 |
| Paris .. | 3·2 | 127·8 | 126·7 | 127·2 | 129·3 | 2·6 |
| Poldhu .. | 2·8 | 230·6 | 230·5 | 232·9 | 229·3 | 3·6 |
| Nauen .. | 3·2 | 77·0 | 76·7 | 78·7 | 70·0 | 8·7 |
| Cleethorpes | 4·0 | 35·9 | 37·2 | — | 36·2 | 1·0 |
| Moscow .. | 5·0 | 63·8 | 63·8 | — | 64·7 | 0·9 |

The results are sufficient to show that comparatively large changes in apparent bearing are produced by a small change in position of the directional receiver, thus confirming those obtained at Teddington and referred to earlier in the paper. Further changes could probably have been produced by other movements of the receiver, but this was not considered to be justifiable owing to the scattered positions of the trees. It was not possible to make any observations with the receiver erected in a clear position on either side of this clump of trees, owing to the intervention of other obstacles, e.g. iron buildings, overhead wires, etc.

It is perhaps significant that in the majority of cases in the above table the most accurate bearings were obtained at the top of the tower, a result to be expected since the induced current in the trees (and hence the resulting field) will be a maximum at the base.

### (5) BUILDINGS.

It has long been known that large buildings, hills and mountains act as partial obstacles to the passage of electromagnetic waves, and the tendency is for the latter to be deviated around the obstacle. A directional radio receiver in the neighbourhood of such obstacles would therefore be expected to give some erratic results. If the building, moreover, contains an appreciable amount of metal work in its construction, such as steel girders, lead or iron roof, etc., an error will result due to their presence, as discussed earlier in the paper. The effect of working inside a building was well demonstrated in one case, where the receiving set was temporarily erected in one of the University laboratories for the purpose of making practice observations. The errors in the readings obtained ranged up to more than 30°, whereas when the set was removed to its final position in an open field less than ½ mile away, the maximum permanent error experienced was 2·8°. In another case, however, where the set was erected at the top of a stone tower about 60 ft. high, from which all the metal work had been previously removed, the maximum deviation error experienced was about 3°.

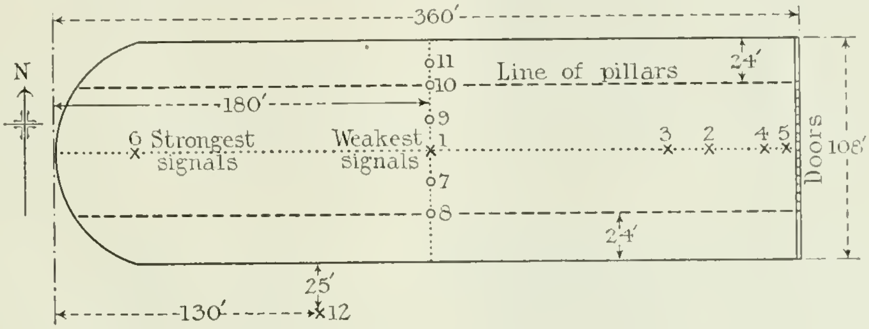


FIG. 5.—Plan and dimensions of "A" shed, Royal Aircraft Establishment, Farnborough.

*Experiments in a large iron shed.*—As a special case of the effect of a building on observed bearings, the results of the following experiments carried out in a kite-balloon shed at the Royal Aircraft Establishment, Farnborough, are of considerable interest.

A systematic investigation was carried out to determine the direction of the resultant field inside the shed by the same method employed in the investigation on the effect of trees and other experiments already described. A plan of the shed showing the positions where observations were made is shown in Fig. 5. Although only a rough estimate could be made of the strength of the signals received, some marked variations were noted in the different positions employed. It was found that at the centre position 1 the reduction of signals was very great, but that as either end was approached the strength of signals became steadily greater, though it was not until the set was brought actually outside the shed that the full strength was attained. Position 6, however, some 40 ft. from the "blind" end gave signals which were obviously much stronger than those at any other position. There appears to be no obvious reason for this, but it is suggested that the curved end might have had some sort of focusing action on the waves. No change in signal strength could be detected on opening or closing the doors of the shed in any of the positions explored.

TABLE 8.

*Apparent Bearings observed at Centre of Shed. Position 1.*

| Station observed | | Wave-length | True bearing | True bearing relative to shed's axis | Error in observed bearing |
|---|---|---|---|---|---|
| | | km | degrees | degrees | degrees |
| Paris | .. | 2·6 | 139·8 | 47·8 | + 12·2 |
| Paris | .. | 3·2 | 139·8 | 47·8 | + 15·0 |
| Nantes | .. | 2·8 | 188·0 | 96·0 | − 14·0 |
| Horsea | .. | 5·0 | 202·0 | 110·0 | − 8·0 |
| Poldhu | .. | 2·8 | 248·0 | 156·0 | + 0·3 |
| Moscow | .. | 5·0 | 64·0 | 332·0 | − 6·0 |
| Nauen | .. | 5·0 | 75·6 | 343·6 | − 13·6 |

The influence of the shed on the apparent bearing of the station observed was carefully recorded in each case, and is here given in Tables 8 to 11.

It was thought most suitable to limit the positions explored to points on the long or short axes of the shed.

Table 8 shows the errors in the apparent bearings observed at the centre of the shed, indicating that the incoming waves are deflected towards the perpendicular to the sides of the shed; the deflection varying from 0·3° to 15°, according to the angle made by the incoming waves with the axis of the shed. No effect due to opening the door was observed on any of the stations.

In Table 9 the effect at different positions along the long axis of the shed is shown, signals from Paris only being observed. These results show that at positions other than the centre the apparent bearing is deflected towards the axis of the shed. The effect is more clearly seen in Fig. 6.

TABLE 9.

*Bearings of Paris (both Wave-lengths) taken on Axis of Shed.*

| Position No. | Distance from door of shed (E end) | Error in observed bearing | | Change in bearing on opening door |
|---|---|---|---|---|
| | | (a) with door closed | (b) with door open | |
| | ft. | degrees | degrees | degrees |
| 5 | 3 | − 21·3 (2·6 km) | − 1·6 (2·6 km) | + 19·7 |
| 4 | 12 | − 20·8 (3·2 km) | − 14·0 (3·2 km) | + 6·8 |
| 2 | 40 | − 19·8 (2·6 km) | − 15·8 (2·6 km) | + 4·0 |
| | | − 12·5 (3·2 km) | — | — |
| 3 | 60 | − 3·8 (2·6 km) | — | — |
| | | + 7·4 (3·2 km) | — | — |
| 1 | 180 | + 12·2 (2·6 km) | + 11·9 (2·6 km) | − 0·3 |
| | | + 15·0 (3·2 km) | — | — |
| 6 | 320 | − 28·3 (2·6 km) | − 27·7 (2·6 km) | + 0·6 |

TABLE 10.

*Bearings of Other Stations taken on Axis of Shed.*

| Position No. | Distance from door (E end) | Station | Error in observed bearing | |
|---|---|---|---|---|
| | | | (a) with door closed | (b) with door open |
| | ft. | | degrees | degrees |
| 1 | 180 | Poldhu | + 0·3 | — |
| 6 | 320 | Poldhu | + 4·5 | — |
| 2 | 40 | Coltano | − 3·0* | + 4·7 |
| 6 | 320 | Coltano | − 24·6 | — |
| 1 | 180 | Horsea | − 8·0 | — |
| 2 | 40 | Moscow | + 25·0* | + 26·0* |
| 1 | 180 | Moscow | − 6·0 | — |

* Indicates night reading.

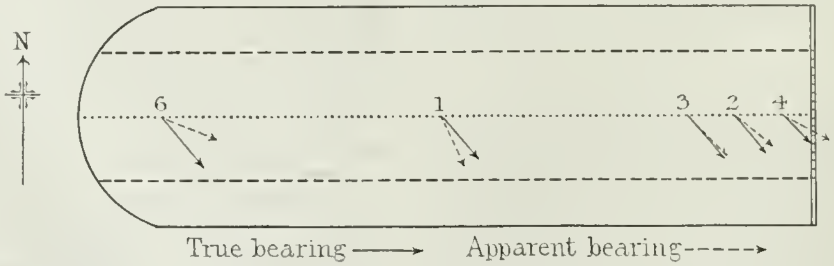


FIG. 6.—True and apparent bearings of Paris at various positions on the axis of the shed (see Table 9).

Table 10 shows the same effect occurring on a few other stations which were observed, thus demonstrating that the results for Paris are repeated for other directions.

Table 11 gives the results of exploring positions along the lateral axis of the shed, showing that for positions north of the long axis the rotation of the apparent bearing is greater than at the centre, while in the southern positions it is considerably less. It should be pointed out, however, that there are two parallel lines of iron pillars supporting the shed and that in Positions 7, 8, 10 and 11 they are near enough to the direction finder to affect seriously the readings obtained.

TABLE 11.

*Bearings of Paris taken on the Lateral Axis of the Shed.*

| Position No. | Distance from N side of shed | Error in observed bearing | |
|---|---|---|---|
| | | (*a*) with door closed | (*b*) with door open |
| | ft. | degrees | degrees |
| 11 | 14 | + 14·0 (2·6 km) | — |
| | | + 15·9 (3·2 km) | — |
| 10 | 24 | + 17·7 (3·2 km) | + 15·0 (3·2 km) |
| 9 | 39 | + 18·1 (3·2 km) | |
| 1 | 54 | + 12·2 (2·6 km) | + 11·9 (2·6 km) |
| | | + 15·0 (3·2 km) | |
| 7 | 69 | + 4·5 (2·6 km) | + 3·7 (2·6 km) |
| 8 | 84 | + 0·2 (2·6 km) | — |
| | | − 1·2 (3·2 km) | — |
| 12 | 133 (25 ft. beyond S side of shed, i.e. outside) | + 16·2 (2·6 km) | — |
| | | + 17·2 (3·2 km) | — |

Position 12 in Table 11 was outside the shed about 25 ft. from the south side (see Fig. 5): it will be seen that here too there was a considerable rotation of the apparent bearings towards the perpendicular to the side of the shed.

A brief survey of all the results obtained in these experiments shows that, in general, the apparent bearings of the incoming signals are rotated towards the normal to the nearest plane surface by an amount which increases as that surface is approached. Fig. 6 clearly shows this. The slight departure from this rule shown in Table 11 may be easily accounted for by the pillars already referred to.

In addition, it was proved that the opening of the large doors had a scarcely noticeable effect on the bearings, except when the set was very close to them (when the result was merely what would have been predicted by the above theory), and had no effect at all on the strength of the signals. This seems to show that no appreciable extra energy comes through the doors when they are open.

### CONCLUSIONS.

Owing to the great variability in the possible nature and disposition of the surroundings of a direction-finding installation, it is very difficult, if not impossible, to make general rules as to the effect of such surroundings. It is believed, however, that the results of the investigations given above are of value in augmenting the scanty evidence previously existing as to the distortion produced in the propagation of electromagnetic waves by various obstacles on the earth's surface.

The experiments themselves suggest further lines of advance, and it is proposed to continue these as soon as opportunity permits.

These investigations were carried out for the Radio Research Board by the authors under the direction of the Sub-Committee on Directional Wireless, the members of this Sub-Committee being as follows:—Mr. F. E. Smith, O.B.E., F.R.S. (*Chairman*); Mr. N. P. Hinton, B.Sc.; Mr. C. E. Horton, B.A.; Captain C. T. Hughes, M.C., R.E.; Captain J. Robinson, Ph.D., M.B.E., R.A.F.; Mr. R. L. Smith-Rose, M.Sc.; and Mr. O. F. Brown, M.A., B.Sc. (*Secretary*).

## DISCUSSION BEFORE THE WIRELESS SECTION, 8 NOVEMBER, 1922.

**Dr. J. Robinson:** The information contained in this paper is of a type that is needed in order to attain the end for which all wireless engineers are striving, namely, that navigators shall have confidence in direction-finding. The paper shows the importance of choosing the correct site for direction-finding apparatus. An examination of the cause of errors brings several points to light. Errors may be produced, as the paper suggests, owing to the fact that some of the factors, e.g. electric force or magnetic force, are not in the direction they are generally supposed to be, while, on the other hand, errors may be due to the fact that some portions of the waves are reflected, giving, at any particular point, an effect of waves arriving from one station in two directions. That leads us to one of the experiments described by the authors. If one set of waves comes horizontally, direct from the transmitting station, and the other is reflected from the Heaviside layer, how are these two sets to be separated? In optics we have the analogy of the telescope, and it was thought that it might be possible to have a wireless telescope. It is known that for a telescope the wave-length should be small compared with the dimensions of the telescope. It is difficult to obtain a mirror or telescope with dimensions many times greater than the ordinary wave-length in wireless, which varies from 200 m to 2 000 m; and the best thing that can be obtained is an airship shed, the dimensions of which are comparable with those of wireless waves. The experiments carried out in the Farnborough airship shed unfortunately did not give the effect of a wireless telescope. I should like to place on record one occasion where an effect was observed which appeared to indicate the possibility of a wireless telescope effect. In an airship shed at Cranwell signals from Paris were weak, whilst those from Nauen were strong. The axis of the shed was nearly in the direction of Nauen and approximately perpendicular to the direction from Paris. Present-day direction-finding is based on the assumption that the magnetic force of the waves is horizontal. The paper gives examples which show that when the magnetic force is not horizontal the bearings are wrong. In the case of overhead wires the authors point out that the magnetic force might be in various directions. In fact, it is probable that at about 100 yards from the telegraph wires the magnetic force might be horizontal, while it might become almost vertical nearer the wires, in which case the direction-finding coil on a vertical axis would give no indication of bearing. It is to be hoped that the time is not far distant when the facts set out in the paper will be appreciated and made use of, and when navigators will know when to expect errors and when to expect accurate readings; then they will place the same reliance on direction-finding as they now place on the magnetic compass.

**Mr. J. Hollingworth:** In observations such as the authors have made, it is extremely difficult to modify the face of the earth to suit experimental purposes and to find sites where the only probable disturbing cause is the one required to be measured. Moreover, as the authors state, it is extremely difficult to make calculations, because the sizes and shapes of the objects dealt with are so irregular that it is impossible to lay down any mathematical law in regard to them. There are one or two special points to which I should like to call attention. At the foot of page 179 the authors truly remark that in some cases "it may be necessary to avoid all possible errors at the site of the installation." I am concerned with a rather important example of that at the moment. When making measurements on an aerial one generally allows for the absorption effect in the immediate neighbourhood, as this is involved in most methods of measuring the effective height, whereas with a coil one usually works on the area-turns of the coil, in which case nothing is allowed for absorption in the immediate neighbourhood, so that whenever a comparison is to be made between coil work and aerial work it is very important to choose an almost perfect site for the coil itself. The authors exhibited a slide showing Bushy House. I myself have an apparatus installed there to measure signal strength, and there is no doubt that the trees in the vicinity have a very considerable effect. I have frequently noticed that when the trees are thoroughly wet my readings are affected, and I think that the trees then form an almost complete screen, because most of the signals with which we have to deal come from the south through a big bank of them. I think that may also be the reason why the particular aerials shown in the diagram do not greatly affect the signals, because, after all, they are on the opposite side of the receiving set to the incoming signals. If the set had been put on the other side of the aerials, the effect would probably have been very much greater. I can confirm what the authors say about the sudden change caused by telephone wires. In my own case, I was 100 feet from the wires, and, owing to the ground not being level, my coil was on almost exactly the same level as the wires themselves. The variations obtained were only of the order of 2°, but they were quite definite jumps; they could not be explained by any general physical characteristics of the atmosphere. There is, I think, no doubt that the effects are due to the operation of the telephone exchanges; capacities which are quite negligible for telephone purposes are considerable for wireless purposes. For the latter I have always considered telephone lines to be practically earthed at the two exchanges in the immediate neighbourhood. My own results were obtained with telephone wires very much shorter, because $\frac{1}{4}$ mile away from the scene of my observations they entered a submarine cable which was practically an earth for wireless purposes. They did not, I think, extend for more than a few miles in the other direction. I am of the opinion, therefore, that it is the near proximity of wires that caused the trouble, rather than any particular length of them. There is one point which I should like to mention with regard to airship sheds. I have in mind some measurements made in an airship shed when all the signals appeared to enter along the axis of the shed—an experience contrary to that obtained by the authors. The shed in question was larger than that used by them, i.e. about 700 ft. long. It was not systematically explored; observations were not taken all over the shed. The fact that a 600-ft. airship containing a great amount of metal work was in the shed, and that the coil itself was standing practically on the keel of the airship, may have modified the conditions very much as compared with those given in the paper, where the shed was empty and it was possible to explore the whole of it.

**Mr. J. E. Taylor:** The paper contains the results of a great deal of work, and the most interesting feature of it, to my mind, is that dealing with variations in the apparent direction of fixed stations, which may be due to local or other causes. The only point on which I wish to comment is in connection with variations observed to be due to the presence of banks of telephone wires. Of course, it is not strictly accurate to say that these wires are earthed at the exchanges, but I think that Mr. Hollingworth has put that right. The wires are practically earthed at the stations to high-frequency currents, not as a result of switching operations but due to the fact that they are led-in in cables, and therefore for wireless purposes we can regard them as being earthed. I feel rather sceptical, however, with regard to the surmise that changes in the apparent direction are due to switching operations at exchanges, which in the case of the Slough experiment are probably quite a distance away from the scene of operations. I feel that that point, in common with many others in the paper, is well worth further investigation. I doubt whether the explanation given in the paper is correct, and it seems to me that it should be a comparatively simple matter to erect on light poles a special pair of wires which would be fixed and not subject to switching operations. Such wires must of course be fairly long, e.g. about 1 mile. If that were done

I should not be surprised to find the variations still in evidence.

**Mr. C. E. Horton:** I was particularly interested in the account of the results obtained on the survey ship "Fitzroy." In this case the dimensions of the coil were small as compared with those of the adjacent metal structures, which are for the most part somewhat irregular. Under these conditions it seems to me rather striking that the curve should approximate so closely to the quadrantal type. I was also rather surprised to see that its magnitude amounted to over 20°. Prof. Mesny, who did a good deal of work with small coils on board ship, usually found quadrantal errors of 8° or 10° on small ships, but in his case the coil was usually placed right aft. I should be glad if the authors would give further details as to the actual position of the coil on the ship, particularly with reference to the funnels. It is stated in the paper that the quadrantal error is independent of the wave-length. So long as the metal structure is small compared with the wave-length, and so long as dielectric currents are neglected, that would be, I suppose, in accordance with theory; but if the quadrantal error amounts to 20° or more, although it is perfectly constant and can in a sense be allowed for, there is some difficulty in making use of it. If the reading of the frame coil is uncertain to a degree or so, i.e. the amount of correction to be applied is unknown, it follows, I think, that when the correction changes rather rapidly, as it does in this case, the final result, after the correction has been made, may be quite incorrect, in fact, more so than the actual uncertainty of the reading itself. It follows, therefore, that a large quadrantal error is very undesirable. As the effect of local structures is so very important when the coil is small, it seems to indicate that what is needed is a system large in comparison with structures in the immediate vicinity. Under those conditions a sort of average effect is obtained, and errors due to small structures are very much decreased. I am thinking now of the Bellini-Tosi system which appears to offer some advantage in the case of a ship, since the area comprised by loops is very much larger, and a much better average effect is obtained. The authors remark that the quadrantal error curve is shifted along the axis some 5° or 6°, that is to say, whereas one would expect to get the zero correction for waves at readings of 0°, 90°, 180°, etc., actually there is a small correction of 5° or 6°, and that is attributed to the effect of small local structures. That again, to my mind, seems to indicate that what is needed is an aerial system much larger than the ordinary frame coil for use on steel ships.

**Major H. P. T. Lefroy:** Errors in direction-finding can conveniently be considered under the headings "uncontrollable" and "controllable," the latter of which can again be conveniently considered under the headings "environment" and "apparatus." This paper deals with some of the errors due to environment, and is an interesting summary of investigations carried out by the authors for Sub-Committee C of the Radio Research Board, in connection with those special errors. Their results show that, when siting and constructing a direction-finding station, it is best to give a wide berth to all possible causes of distortion, in and around the station. As regards lines, in ordinary practice one has to use electric power and light, and to have a telephone. The practical problem then raised is: Shall the lines be put underground or run overhead? I noticed that the authors' lines went past the station and did not terminate there, as they nearly always do in practice. It would be instructive if some figures could be obtained showing the difference in the errors caused by lines buried 3 ft. deep, and lines brought in 10 ft. or 12 ft. overhead, as they usually are, and terminating at the station itself. I should like the authors to say at what time of the year the experiments with trees were carried out. From the botanical point of view it would be interesting if they could take a series of measurements once a week, or once a fortnight at a certain definite spot, e.g. position XI, to find out how the errors due to the trees change with the seasons and the state of the foliage.

**Mr. G. M. Wright:** On page 179 the authors dismiss very summarily the question of night effects by saying that "little is known as to the causes producing these effects, though much has been surmised." Mr. Eckersley has published a paper * on the subject of night effects in which he sets forth a theory which, besides being reasonable, has the advantage of being well supported by the experimental results obtained up to that date. Since then, further investigations have been made † as to the behaviour of the cardioid diagram of reception under the influence of night effects, and these investigations have afforded the most striking confirmation of Eckersley's theory. I know of no other theory which has been seriously proposed and examined which rests on so sure a basis and is capable of affording so complete an explanation. I would also point out that the minimum of a cardioid diagram remains unchanged and correct throughout the most violent night effect and affords a practical means of direction-finding under these conditions. In fact, any directive receiving system which presents no unbalanced horizontal members to a ray incident in the direction of zero reception is capable of being used as an accurate direction-finder in the presence of night effect. I should also like to draw attention to the similarity of the curve shown in Fig. 1 (*b*) to a simple sine function. This resemblance affords a very easy method of correcting the errors when using crossed frames in conjuncton with a radiogoniometer. The method was proposed some years ago by Captain Round, and consists in placing one aerial in the plane towards which the bearings are distorted. A suitable reduction in the receiving power of this aerial will then give the required correction. Under all ordinary circumstances the correction obtained in this way is sufficiently accurate, and no error chart is required.

**Admiral Sir Henry Jackson:** There is a great deal more work to be done in this direction, especially in connection with short waves. I think that it would be desirable to carry out similar experiments with trees, telegraph wires and large metallic objects with short waves, such as are used for navigational work. The object of the Radio Research Board is to try to define the different errors, so that we can correct our direction-finding apparatus in ships as the magnetic compass is corrected. We are now in the early days of direction-finding and I hope that in a few years direction-finding at sea by wireless will be as accurate as it is now by compass.

---

* "The Effect of the Heaviside Layer on the Apparent Direction of Electromagnetic Waves," *Radio Review*, vol. 2, pp. 60 and 231.

† "The Heart-shaped Polar Diagram and its Behaviour under Night Variations," *ibid.*, p. 394

**Major B. Binyon :** I was very interested in the description of the work done on board ship, and I hope, with Admiral Sir Henry Jackson, that the work of the Radio Research Board will be further extended in that direction, because, from a commercial point of view, it is one of the most important fields in which to work. It is to be regretted that in most of the work done on ships, data for which are given in the paper, fairly long waves have been used, whereas in practice it is absolutely essential that direction-finders to be really useful should work mainly on 600 m. Mr. Horton stated that, in his opinion, better results would be obtained with an aerial system than with coils on ships. I should like to mention, in that connection, that a number of ships have been fitted with Robinson direction-finders, and the extraordinary accuracy of the results obtained is proof of the reliability of a coil system aboard ship, particularly when the exceedingly difficult conditions are taken into account—conditions far more difficult, I think, than any of those described in the paper. Again, quadrantal errors as large as 22° are referred to in the paper. I have never known such an error on a ship fitted with the Robinson system ; I can recollect one case where an error of 19° was obtained, but in the case of another steamer where the conditions were similar the quadrantal error was nil. In the latter case the quadrantal error remained nil until, after a long trip, the boat was nearing home, when suddenly an error of 6° or 7° developed. No explanation was forthcoming at first, but the trouble was eventually traced to four electric leads used for emergency communications between the chart room and the emergency steering position aft. These leads were supposed to be absolutely dead, but somehow or other a fault had developed in them, and small currents from the electric light circuits leaked on to them. They were eventually shown to be entirely responsible for the error. That is an instance of the sort of problems that have to be faced in shipping work and which increase the difficulties. In spite of this, however, there is no doubt that exceedingly good and satisfactory results can be obtained with the Robinson system on board ship. The constancy of the quadrantal error is, of course, all-important and has to be very carefully watched for, but on the whole the changes are very slight. As a matter of fact, a discrepancy was observed in the case of a ship that went out quite light—in ballast—and returned very heavily laden. In that case the quadrantal error on the return journey had diminished by a small amount. Unfortunately, experimental work on ships of the mercantile marine is exceedingly difficult to carry out, and it can more systematically be done by the Radio Research Board or the Admiralty allocating vessels for the purpose. With the extended use of direction-finders, however, exceedingly interesting data of this nature is gradually being collected. I should like to support Admiral Sir Henry Jackson's suggestion that more work should be done on short wave-lengths, in order as far as possible to benefit directly the commercial application of direction-finding as an aid to navigation.

**Captain C. T. Hughes :** I should like to call attention to the importance of the information given in the paper from the military point of view. It might possibly be urged that a radio engineer entrusted with the installation of a direction-finder would never deliberately put up his set in the neighbourhood of trees, buildings or other wireless aerials, but in military practice it might be impossible to avoid doing so. As direction-finding is a vital part of military wireless, it is very important that one should have every possible scrap of information regarding the errors to be expected owing to the presence of these disturbing elements. It very frequently happens that a wireless officer has no choice of site in putting up his direction-finder ; there are a large number of considerations, chiefly military, which hamper his selection of suitable ground. For example, it is essential that he should have a means of rapid communication, by telephone or ordinary telegraph line, with the intelligence centre to which he has to send his information. It frequently happens that it is very difficult to provide a special line for him, and possibly he has to put up his direction-finder in the immediate neighbourhood of some busy signal office where there are a large number of overhead lines or buried cables. It might be inadvisable, moreover, to put a direction-finder in an isolated field, well away from trees and buildings, from the point of view of visibility from aircraft. That is only one of a large number of considerations which must influence the selection of a site. Major Lefroy, I think, rather dismissed the possibility of errors due to the proximity of overhead lines, by assuming that the lines were the actual supply mains or line communications of the station itself, and that these are generally controlled by the officer in charge of the station and can be buried for some hundreds of yards away from the direction-finder. The officer may be obliged, however, in times of rapid military movement, to erect his set in the near neighbourhood of large permanent routes on a main road, or other disturbing factors may appear in the shape of large masses of metal such as ammunition dumps. In military wireless too, the set has frequently to be handed over to semi-skilled personnel who have had little chance of acquiring a knowledge of what constitutes good conditions for direction-finding. For these reasons we welcome any information that tends to define the conditions governing the installation of a direction-finder or gives us a knowledge of the magnitude of the errors to be expected under adverse conditions of working.

**Major C. J. Aston :** I should like to ask whether anything is yet known as to the effect of rivers on direction-finding. It is often necessary to erect a direction-finder in the neighbourhood of a river, which might have a straight course 3 to 4 miles in length, and might influence the direction of the arriving waves. The Army of Occupation in Germany found such conditions at Cologne.

**Dr. A. Russell:** Have the authors considered the effect of meteorological conditions on the direction of reception? For instance, on one side of the direction-finder there may be a shower of rain, while the other side is dry. The trees on the one side would be almost perfect conductors under such conditions, while those on the other would have a very high resistance. We know that the resistance of the surface of the earth varies to a very large extent with the amount of dew on it. It would therefore be interesting if the authors could give any information on this subject.

**Mr. S. B. Smith** (*communicated*): It can be demonstrated that if a directional system be constructed in such a manner that no unbalanced horizontal members exist, then abnormally polarized waves will not be received. With such arrangements it can be experimentally shown that when night effect is present the bearings are correct. The minima will also be quite symmetrical, and the arrangement provides a practical direction-finder. A number of anti-" night effect " direction-finders (which possess symmetrical minima) exist, among them being Adcock's modification to the Bellini-Tosi aerial system, and Franklin's spaced aerials (arranged in the Bellini-Tosi manner). These methods are well known and do not require further detailing, but at the same time it should be pointed out that it is quite practicable to construct a direction-finder to be quite immune from " night effect " or the closely related " aeroplane effect." In Section 3 of the paper the authors discuss tuned aerial systems and their effect when in close proximity to the direction-finder. No mention is made of the importance of the resistance of these aerials, but unless the authors give the dimensions of these aerials and their resistance the observations are comparatively useless. At a recently installed direction-finding station the apparatus is erected underneath the main transmitting aerial; if this aerial is accidentally tuned while the direction-finder is in operation the maximum observed errors amount to 30°. If the tuned aerial had a very low resistance (principally radiation resistance) the maximum deviation from the true bearing could amount to almost 90°.

**Messrs. R. L. Smith-Rose** and **R. H. Barfield** (*in reply*): The discussion has, in general, shown that the paper has met a real need for detailed quantitative information on this subject. There is a general consensus of opinion as to the necessity of repeating the majority of the investigations on much shorter wave-lengths, and it is intended to proceed with this work as quickly as possible. The research was inaugurated on the higher wave-lengths for no other reasons than those of convenience and expediency, since suitable apparatus was immediately available. The experience gained so far will undoubtedly prove useful in the work on shorter waves where the difficulties of accurate radio direction-finding are somewhat greater.

Mr. Hollingworth mentions a case of a large airship shed in which all the signals appeared to enter along the axis of the shed. This is exactly the conclusion that might have been drawn for the shed referred to in the paper when at Position 6 in Fig. 6, had not the results obtained in other positions been contradictory.

The results given for the experiments carried out on H.M.S. " Fitzroy " were certainly obtained under very bad conditions. The direction-finding coil system was erected in the only place available on board, being placed fairly close to the ship's funnel and the wireless cabin, and standing on the steel deck. Mr. Horton expresses surprise at the magnitude and regularity of the error curve, yet a somewhat similar curve has been given by Mr. Round for H.M.S. " Warspite," and cases are mentioned in which the error curve ranges up to 30°.[*] Regular quadrantal error curves have also been obtained in America when using small frame coils on board ship.[†] The results given in the paper for H.M.S. " Fitzroy " have been confirmed by later observations and the error has been found to be practically independent of small metal work in the immediate neighbourhood, e.g. the error remained unaltered by opening and closing steel hatch covers immediately beneath the set. The disadvantages of a large correction curve for navigation purposes are fully appreciated, but it is probable that the magnitude of the error could be considerably reduced by erecting the frame coil in a more suitable position on board and particularly by raising it several feet above the deck. The present paper is not concerned with the relative merits of the Bellini-Tosi and the frame-coil systems of direction-finding on board ship, but it may be pointed out that considerable use of the single frame has been made in America.[†]

The point raised by Major Lefroy as to the comparative effect of overhead and underground lines actually brought into the direction-finding station is one that has not so far received attention but is obviously important for practical purposes. It is hoped to obtain much information on the influence on the resulting errors of the seasonal change in trees from an investigation which has been proceeding for some time past, involving the daily observation of various transmitting stations in fixed positions. The influence of meteorological conditions mentioned by Dr. Russell will also be studied in the same investigation.

In reply to Mr. Wright, the authors feel bound to uphold their original statement to which reference is made. While fully recognizing the utility of the brilliant work carried out by Messrs. Eckersley, Wright and Smith, it must be mentioned that there are already some apparent exceptions to Eckersley's theory concerning variations.[‡] Beyond this fact, the paper is not concerned with these night variations in the bearings observed on direction-finders. As to the use of circuits giving the cardioid-diagram reception curves to overcome these effects, this has surely never been claimed as a practical system of direction-finding. At the best, it affords a convenient means of determining the " sense " of a bearing.

That there are certain methods, theoretically sound and experimentally successful, of eliminating abnormally polarized waves is beyond question, nor can it be denied that it may be possible to construct a commercially practical apparatus for this purpose. It is merely contended that as yet this has not been done. Mr. Smith mentions two systems, those of Adcock and Franklin, but Mr. Keen in his recent authoritative work on direction-finding * dismisses the Franklin system as being "impracticable for ordinary direction-finding working" giving convincing reasons, whilst Adcock's system has never been taken up owing to its inherent difficulties. As regards tuned aerials, a record of what actually happened in one or two specific cases was thought to be of sufficient value in giving the order of the possible error to merit recording. For example, Mr. Smith's own instance is of some definite interest though it would have been of more value if he had given the distance of the direction-finding set from the aerial.

---

[*] *Journal I.E.E.*, 1920, vol. 58, p. 243.

[†] See, for example, S. Ballantine: *Year Book of Wireless Telegraphy and Telephony*, 1921, p. 1131; also F. A. Kolster and F. W. Dunmore: *Scientific Papers of the Bureau of Standards*, No. 428, 1922.

[‡] See, for example, E. Bellini: *Electrician*, 1922, vol. 89, p. 150; also R. Mesny, *L'Onde Electrique*, 1922, vol. 1, p. 501.

Major Binyon's request to investigate directional reception on board ship on the waves ordinarily used for ship communication is covered by the proposal to extend the whole investigation to short-wave working.

The possible effect of rivers, mentioned by Major Aston, is also a case for future investigation.

---

* R. Keen: "Direction and Position Finding by Wireless," 1922, p. 195.

# DOMESTIC LOAD BUILDING: A FEW SUGGESTIONS UPON PROPAGANDA WORK.

By W. A. Gillott, Associate Member.

(*Paper first received 11th September, and in final form 13th October,* 1922; *read before* The Institution 30*th November, before the* North-Eastern Centre 27*th November, before the* Liverpool Sub-Centre 11*th December, before the* North Midland Centre 19*th December*, 1922, *and before the* Scottish Centre 9*th January*, 1923.)

## Summary.

The object of this paper is to show in a simple manner some of the channels open to electric supply undertakings for securing the domestic load. As conditions differ in almost every district, the subject must be approached from a different angle in each case. In certain districts it might be fatal to adopt a too progressive attitude, and one must therefore lead up to the point by suggestion; in others it may be found desirable to combine the development scheme, such as an educative campaign by actual demonstration, with Press and other advertisements. These methods are briefly discussed and reference is made to the value of the load to the undertaking, and the various proportions it can take. A skeleton scheme of one year's campaign is put forward, and, in view of the decision of certain authorities to embark upon this development, it is hoped that the remarks may be of interest. The fundamental essentials on the question of tariffs, load characteristics, hire of appliances, etc., are discussed, and a chart showing one week's demand of a housing estate, where cookers, heaters, etc., are installed, is given. The advantage of an electrically equipped household to the consumer and its appeal to women, also the assistance given by the latter in achieving the object, are referred to.

## Fundamental Principles.

The increasing tendency of the housewife to do her domestic work by means of electricity is most encouraging, and indicates that the excellent propaganda work of the Electrical Development Association, electric supply authorities, electrical contractors and manufacturers is at last beginning to show a return. These promising conditions prompt the author to offer a few suggestions in regard to domestic load-building to those engineers who have not yet attempted to cultivate this desirable and profitable demand. At the outset he would like to state that his remarks are not put forward as definite proposals as to how matters should proceed, but merely as a suggested principle upon which the framework of an organization or department can be constructed to deal with the business.

The first matter that should receive attention is the personnel. From the chief engineer to, at least, the sales representatives each individual should possess an adequate knowledge of the subject of domestic electrification before attempting to advise others. In addition, an electrical installation, complete in every detail, should be in the homes of such members of the staff to enable them to gain valuable experience and thoroughly to appreciate their operation. It would also establish a belief in the commodity and be an encouragement to prospective consumers.

It is desirable to keep a careful set of records of the behaviour of each type of appliance, of the time taken to attain certain objects, of the consumption, also of maintenance costs. By this means a valuable set of statistics would soon be collected which would be of considerable help in establishing a foundation on which to build a suitable scheme. During these observations a complete set of recording ammeter charts should be secured. If several of these are taken simultaneously, a summation curve can be plotted and accurately compared with the station load curve, to facilitate the design of a suitable tariff (if one is needed). Curves similar to these were given by the author in a previous paper.* From these earlier curves the following figures were taken: The number of units per annum per kilowatt installed was 360; the total connected load of the 13 consumers studied was 65 kW, while the maximum demand was approximately 19 kW. The amount of this load that fell on the system peak was 5 kW. The number of units consumed per annum per kilowatt of demand on the system peak was 3 240. The diversity factor was 9. Although these curves were taken some time ago the characteristics remain the same to-day, cooking conditions not having altered. The design of the apparatus is, however, improved, therefore the number of units consumed per kilowatt installed is reduced. A safe figure to adopt for estimating purposes when investigating the subject is 300 units per kilowatt installed per annum. These figures assume a normal daily use throughout the year and are sufficient to indicate that the domestic cooking load is worth cultivating.

## Tariff Construction and Load Possibilities.

It is not intended to study the details of tariffs for this class of business, beyond referring to the desirability of a two-part scheme, with a comparatively high fixed charge, and with the charge per unit so low as to provide a satisfactory return. The author inclines to the opinion that the fixed charge should be sufficient to cover a consumer's normal lighting costs when the low unit charge is added. In other words, his lighting account would be practically identical under this tariff with what it would be under the standard flat rate which may be in operation. This provides a safeguard against supplying the consumer at a loss, and it is only upon an increased consumption that he obtains the benefit of the cheaper units.

Taking as an illustration a domestic consumer with

---

* *Journal I.E.E.*, 1915, vol. 53, p. 42.

1 kW of lighting installed, under average conditions his normal consumption would be approximately 300 units per annum, thus :—

| *Flat Rate* | £ s. d. | *Two-part Tariff* | £ s. d. |
|---|---|---|---|
| 300 units at (say) 8d. .. .. .. | 10 0 0 | Fixed charge per kilowatt (lighting) installed (say) .. .. .. | 8 10 0 |
| | | 300 units at (say) 1½d. .. .. .. | 1 17 6 |
| | | | £10 7 6 |

The figure of 1½d. is taken because the present tendency is to supply electricity for domestic purposes at this rate.

From the above it will be seen that the consumer's lighting account remains, for all practical purposes, unaltered. If such a consumer installs a cooker, catering for 6 persons, his consumption of electrical energy would be increased by approximately 1 750 units per annum, making his account as follows :—

| | £ s. d. |
|---|---|
| Fixed charge as before .. .. | 8 10 0 |
| 2 050 units (lighting and cooking) at 1½d. .. .. .. .. | 12 16 3 |
| | £21 6 3 |

The average price obtained per unit will be approximately 2½d. It is good business to prove to a consumer that his adoption of a domestic or multi-part tariff does not increase his normal lighting account, and that extravagance in the use of light is costing him only 1½d. per unit, which can for practical purposes be ignored. He will then see that his cooking, heating or power is charged at this low rate and he will appreciate the change. The education of the consumer upon this point will be of great value, as he will learn to look upon his supply as being given at 1½d. per unit, and regard the fixed charge as a rental. He will probably spread the news amongst his friends, and this will be good propaganda for the undertaking. Such an installation would create a maximum demand of approximately 3·5 kW, which would occur about mid-day, i.e. at a time when the majority of central stations could deal with the load. Taking average conditions at 200 volts or over, the service cable to a house with such a demand would probably be of adequate capacity, and, therefore, in such cases there would be no additional costs under this heading. It is, of course, recommended that negotiations should be commenced to induce the consumer ultimately to extend his demands for other uses, e.g. heating, water heating and auxiliaries, in which case the service cable would be made suitable. An increase of 3 kW of heating and 2 kW of auxiliaries would make but little difference to the maximum demand, this being approximately 5·5 kW, and then only in winter time, but the total consumption would be in the neighbourhood of 3 500 units per annum, representing, on the basis given above, an amount of £30 7s. 6d., i.e. an increase of £20 7s. 6d. above the ordinary lighting returns.

Taking as an illustration some 500 of such consumers on one system, the maximum load installed would be 6 000 kW; the maximum demand on the station would not, however, owing to the high diversity factor, exceed 600 kW. The consumption of the whole would be 1¼ million units, and the revenue approximately £15 200.

One of the most important characteristics of this class of business is its continuity; in contrast to the industrial load it is unaffected by strikes or lock-outs, and this should therefore increase the desire to cultivate it.

The curves on page 199 indicate the nature of the load upon the Billingham Housing Estate. These curves show the result of the demand of 25 houses only, i.e. approximately one-third of the whole village.

The details of the installation of each house are as follows :—

1 Cooker.
1 Wash boiler (10 gallons).
1 Fire.
Kettle or iron.
Lighting.

The average number of kilowatts installed at each house is 11·28, and, therefore, the total connected load is 11·28 × 25 = 282 kW. The pressure at the consumers' terminals is 250 volts. It will be seen that the highest demand (approximately 31 kW) occurred on Sunday, 11th December, at 12.30 p.m. It is interesting to note that this demand lasted for only a few minutes, the average maximum demand being in the neighbourhood of 24 kW. The returns, being taken in winter time, are consequently at their maximum.

It is of interest to study the characteristics of the daily demand. As the curve shows, Sunday is undoubtedly a day when much cooking is done, and no doubt a certain amount of heating is carried on from breakfast (8.15 a.m.) to 2.30 p.m. There is a short period of rest before tea is prepared, about 4 p.m., and at 6.30 p.m. the load quickly drops to the normal lighting demand, as is the case on each day of the week.

The morning load on Monday and Tuesday is due to the wash boilers and cooking. Monday's curve indicates that the boilers are in operation soon after 8 a.m. and that the cooking load is not so heavy, as probably no mid-day meals will be cooked. On Tuesdays almost the same conditions apply, but more cooking is done, as shown by the demand from 12.30 p.m. to 2 p.m. Thursday is undoubtedly the bread-baking day, as shown by the comparatively longer period of demand. Saturday appears to be a day of "put off" meals.

The occupiers of the houses include district engineers, station engineers, engine drivers, and the usual type of individual employed upon a supply system. No other system of cooking is provided, and it is the usual practice to bake bread and cakes at home.

These curves give much information, and one is able to estimate with accuracy the size of feeder cables necessary for a district. They show at a glance how the load comes on and how it coincides with the general station demand, and they can be applied to any system for comparison. They amply prove the load to be a daytime demand, and that it is continuous, i.e. it is an everyday load. The high diversity factor is well

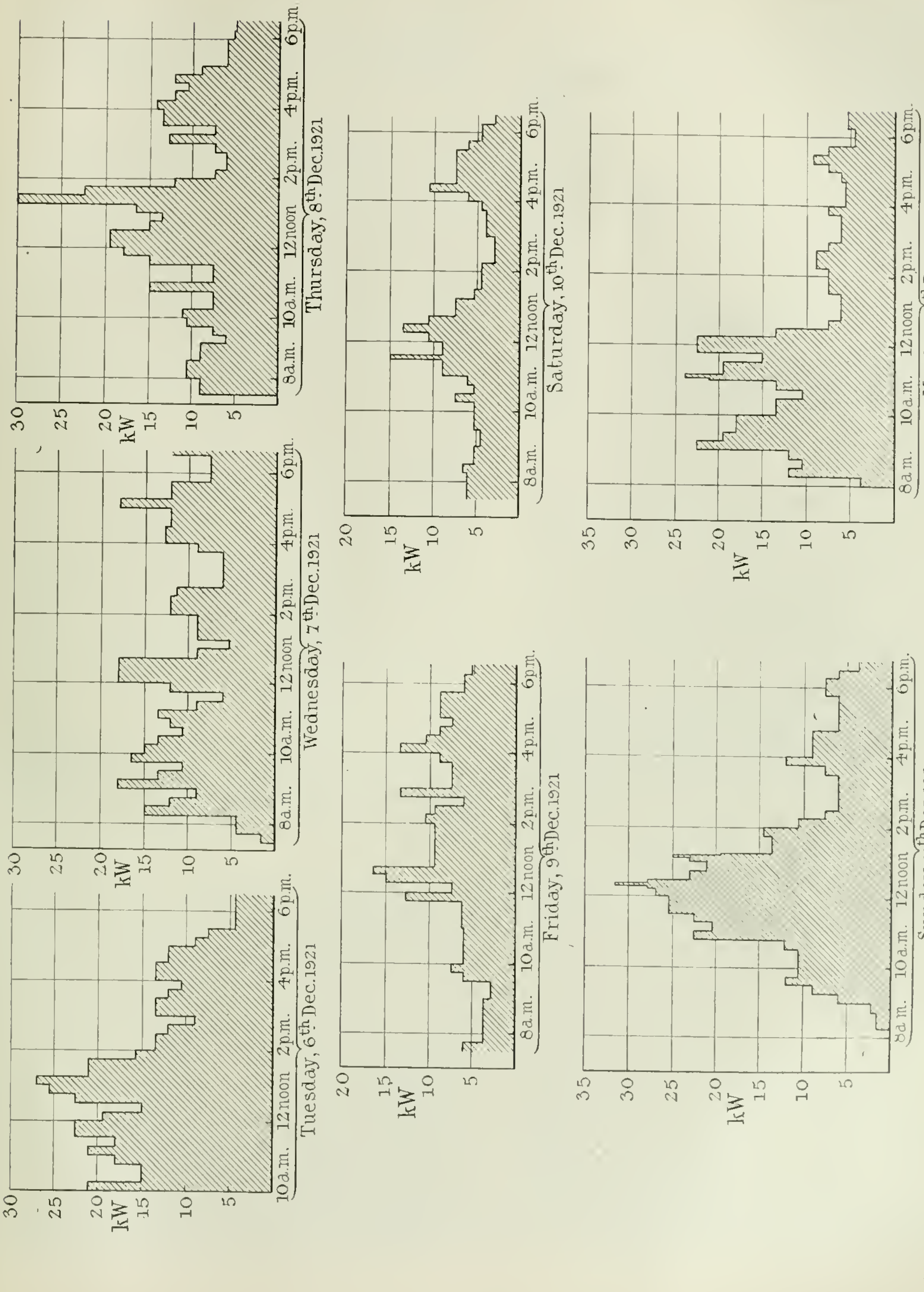


Chart showing one week's demand of a housing estate where electric cookers, heaters, etc., are installed. This represents the result of a *connected* load of 282 kW over 25 houses.
]

demonstrated, and proves the value of the load to an undertaking.

These curves enable one to imagine the nature of the system load in the power station of the future. By multiplying these results by the number of likely consumers in a given area, it will be seen that it is possible for the domestic load in many stations to be larger than the industrial load.

The author has compared the curve for Sunday with that of a gas company's output on a similar day. The two are identical in shape, and it is interesting to relate that the value to the gas company of 5 hours' Sunday's load was equal to that of a whole week-day's combined domestic and industrial load.

In view of the importance of the domestic load, and the desirability of distributing as much information of its character as possible amongst supply engineers, the author suggests that the Institution might consider the advisability of investigating the matter in detail and submitting a report upon its findings. The Electrical Development Association have obtained certain information of a general nature, and by co-operation most valuable assistance could no doubt be given to the industry.

Turning now to commercial cooking, considerable revenue can also be secured from this source. In an earlier paper * the author gave a set of curves showing the load characteristics of four installations, including three staff-feeding kitchens and one restaurant, totalling some 452 kW connected. The total number of units consumed was 290 000 per annum, and the resultant maximum demand was 190 kW (approximately). These facts are important and demonstrate the value of the load.

It is realized that there are many small undertakings which are not at present in a position to handle a big demand for cooking and heating, and that some concerns do not encourage the business as their load is entirely residential lighting and they possibly fear that the cooking business will create a loss. It will be understood that even moderate cooking demands are not built in a day, such loads being secured by a comparatively gradual process. It is suggested, therefore, that a start should be made upon a small scale in order to gain experience in districts where the plant and cable capacity are small and the rate is unsuitable for complete cookers. It will be found that if auxiliary appliances, e.g. kettles, irons, toasters, boiling plates, washing machines, vacuum cleaners, etc., are used, their existence will have a greater effect on the financial returns than on the station maximum demand.

It is not, however, the object of this paper to discuss the technicalities of the load and its effect upon the plant and cables, but to open up various channels that may assist those who are interested in the subject to secure the business. The possibilities of the domestic field are large, and the figures and statistics given indicate a few of the results that can be obtained by negotiation.

There are, no doubt, undertakings in which the domestic load has not been encouraged, possibly because the staff have not studied the subject, or because they are uncertain of the effect of the load on their system and tariff. It is possible for concerns to obtain information, complete in every detail, as to how this load will apply to their own undertakings, and they can in consequence embark upon any such scheme knowing from the commencement approximately what the results will be.

### The Consumers' Gain.

The next point of view to consider is that of the consumer. What benefit will he derive from using electrical energy freely, and will its adoption give him the service he needs?

In the average household of six persons a maid and occasional help are employed, and the installation of electrical appliances permits a reduction of labour charges at least equivalent to the amount spent on electricity. If it should be decided to retain the existing labour, benefit is secured by the relief of heavy and tedious work, better working conditions, convenience, cleanliness and improvement in the health of the family owing to the non-polluted atmosphere and more freedom enabling them to pursue a more out-door life. Unless one has lived in an electrically equipped home it is almost impossible to realize its worth, or to imagine how many household duties entailing laborious work, e.g. clothes and dish-washing, carpet beating, wall cleaning, can be performed by a mere turn of the switch. The author is of the opinion that if men were to study the internal domestic problem more closely, or were called upon to do the actual work, the use of electrical labour-saving appliances would be greatly increased. In works or offices men adopt the principle of "Save the man and use the machine." Why should not this principle be applied at home? The housewife has more to contend with than is generally realized, and it is only fair that she should benefit by the use of the appliances now available.

The items already stated were given to indicate, in a brief manner, the value and magnitude of the possible load. It was felt desirable to give these instances as the good load factor which domestic electrification provides when cookers and heaters are used under normal daily conditions is not generally realized.

### A Skeleton Scheme of Propaganda.

The basic facts being agreed, one can now proceed to commence the campaign. There are various methods available, e.g. the local Press, mailing letters and leaflets, posters, exhibitions, showrooms, personal calls, lantern slides, etc. The amount to be spent on propaganda will doubtless be decided, and upon this will depend the extent of the scheme; the smaller the amount the greater is the care that must be exercised in selecting the medium.

As an illustration, take a town with a population of, say, 100 000, in which the sum of £500 is to be allowed for one year's advertising, it also being decided to adopt a hiring policy for electrical appliances, and to reduce the price of electricity. It is suggested that a staff conference should be held, at which the programme could be discussed to ensure that the campaign should be commenced with at least the majority of the members enthusiastic and co-operating to reach some definite

---

* *Journal I.E.E.* 1918, vol. 56, p. 92.

goal, say 250, 500 or 1 000 kW connected in a specified period.

In the early stages it will probably be found advisable to adopt the least line of resistance by encouraging the existing consumers to increase their demand, and there are other obvious reasons for this procedure.

A saving of expense will no doubt result if a mailing campaign is arranged to coincide with the dispatch of the quarterly accounts, the backs of which should convey a suitable message drawing attention to the reduction in price of electricity, and other special features, and a small booklet should be enclosed to suit the particular period of the year.

Municipal undertakings owning tramways have the advantage in being in a position to exhibit showcards or notices in the tramcars at possibly no expense beyond the printing, thus securing valuable publicity. Lantern slides can be exhibited at the local kinema houses or theatres each week throughout the year. Those slides would doubtless be changed, say, four times per annum at the change of each season.

A productive and economical exhibit can be given by establishing a " Comfy Home " exhibition. For this the loan of a house (which can usually be secured free) is obtained, and the house is then equipped in every detail, thus enabling the appliances to be shown in actual use under normal conditions. If properly handled no difficulty will be met in securing the co-operation of the various trades concerned, i.e. furnishers, decorators, builders, etc., each performing his part at his own cost. Suitable invitations should be sent out, and it is recommended that the editors of the local Press and certain influential people should be invited to an electrically cooked meal before the exhibit is opened. This will probably ensure a valuable report appearing in the Press, and interest will be stimulated.

The electrical contractors of the town could be encouraged to participate in the scheme by dressing their showrooms with domestic appliances so as to fit in with the scheme, and their clients should have every facility offered them to inspect the home, when all details would be explained to them, the contractor being, of course, properly dealt with in regard to any sales effected.

It cannot be too strongly urged that an exhibit of this nature should be arranged to appeal especially to women ; their needs and desires should be studied in every detail, and great care should be taken to give them all the information possible. In addition, they should be encouraged to handle the various devices for domestic use.

It may be found desirable to arrange for private demonstrations on selected days, for the benefit of those who would not care to discuss matters when other visitors are within hearing distance. This will ensure more rapid progress being made. It is advisable at the outset to secure the interest of women, for they will then make it their business to persuade their husbands to complete the transaction. The author's intention is not to suggest that one's efforts should cease at this stage, but to point out that women's influence will be of considerable help in effecting sales, and that its cultivation is worth while.

### General Electrical Exhibition.

It would be helpful if an electrical exhibition could be held, at which manufacturers and contractors would co-operate. A large hall is not necessary for the purpose, as quite good results can be secured with a moderate expenditure, and for small towns a week's duration will probably suffice. Endeavours should be made to show all classes of operations that would be of the greatest assistance and interest to the inhabitants. Arrangements might be made with advantage to establish a series of self-contained exhibits, such as a model kitchen, with cooker, water heater, clothes washer, etc., in operation ; a shoe-repairing shop with the stitching machine and sole-polishing iron electrically operated ; a confectioners' bench with cakes and chocolates made electrically ; a small electric laundry ; and a day and night nursery complete with all requisites from those for rocking the cradle and warming the milk, to an electric sewing machine for making babies' clothes. The object should be, as far as possible, to show something working, as it has a peculiar fascination to the visitor and of course demonstrates in a practical manner the many uses to which electricity can be applied.

It is not suggested that such an exhibition should be held each year, but only as an attempt to popularize some special feature as mentioned above. It will be readily understood that if exhibitions of this nature are held in the same town at too frequent intervals they will become uninteresting and will thus be of little value.

### Details of Expenditure.

The various channels in which the sum of £500 could be expended having been briefly stated, the following will be a guide to their respective costs. In analysing these figures it must be appreciated that the leaflets, posters, show cards, etc., would be purchased through the Electrical Development Association, thereby effecting an appreciable saving. The number of consumers has been assumed at 3 500 for the purpose of making this estimate.

| *Total yearly cost of mailing campaign at each quarter day (four per annum).* | £ | s. | d. |
|---|---|---|---|
| Differences of postages when sending accounts | 58 | 8 | 0 |
| Leaflets .. .. .. .. .. | 40 | 0 | 0 |
| Cost of printing only on back of account forms .. .. .. .. .. .. | 5 | 0 | 0 |
| *Other items.* | | | |
| Lantern slides, rent at 4 theatres, 52 weeks each at 4s. (average price) .. .. .. | 41 | 12 | 0 |
| Cost of slides, say .. .. .. .. | 5 | 0 | 0 |
| Show cards and posters (these would be exhibited upon the undertakings' own property, viz. vehicles, buildings, cable tents, etc.) .. .. .. .. .. | 10 | 0 | 0 |
| " Comfy Home " exhibition .. .. .. | 70 | 0 | 0 |
| Electrical exhibition .. .. .. .. | 150 | 0 | 0 |
| 20 000 assorted leaflets (average price £3 per 1 000) .. .. .. .. .. | 60 | 0 | 0 |
| Local Press advertising (say 10 insertions) .. | 60 | 0 | 0 |
| | £500 | 0 | 0 |

As may be readily appreciated, this schedule can be improved upon; it can also be further sub-divided or cut down if a less costly scheme is desired. It suffices, however, for the immediate purpose of promoting discussion.

### Showrooms.

The use of showrooms to electric supply undertakings is more appreciated at the present time, but it is essential that, to ensure success, these should be properly managed. If there is sufficient space to do so it will be desirable to show different systems of wiring and lighting, and various types of apparatus in as nearly as possible their normal conditions. Interest will be created if certain days or weeks are given up to specific functions, e.g. washing, ironing, cooking, vacuum cleaning, table appliances, etc. Actual working exhibits are preferred, as visitors will be more inclined to discuss proposals than if "dead" shows are given.

It is suggested that all such work of a homely nature should be conducted by a lady demonstrator in such a position that the operations may, upon certain occasions, be seen from the street.

The outside sales representatives should be kept informed as to the callers from their districts, and as much information as possible of their visit should be given to save much ground being covered twice; the consumer appreciates this and it places the salesman upon a better footing.

### Hire of Cookers.

It is not proposed to discuss fully the internal organization necessary for the hire of cookers, but it might suffice to state that if a rental of 20 per cent per annum on the net cost be established it will provide a satisfactory return on the capital invested and will cover the cost of maintenance. Local conditions will, of course, influence these rentals, and in certain districts a much higher return can be obtained.

It must not, however, be overlooked that the mere fact of the cooker being installed and used earns a revenue which without such facility may not be obtained. It is suggested that a lady cook demonstrator should make periodical calls upon the consumers to render efficient cooking service and to ensure that the consumers are securing the best possible results.

Those undertakings where the cooking load is not required so rapidly as when simple hire is established may conduct a hire-purchase scheme, which does not involve as much capital outlay and which will encourage the consumer to handle the appliances with greater care. There are, of course, political conditions that prevent certain undertakings from supplying appliances under this plan, but the formation of a company to conduct such work, as mentioned by Mr. C. H. Wordingham at the Sanitary Congress, would overcome the difficulty and enable a business profitable to all concerned to be established. It is hoped that this suggestion will be followed up and become an accomplished fact.

The chief engineers of central stations usually have their time fully occupied upon the engineering side of the business and have not much opportunity of concentrating their attention on the commercial end. The author hopes, therefore, that these suggestions will be acceptable to them. He has given a good deal of consideration to the domestic load question and fully realizes that these remarks only touch the fringe of the subject. In suggesting that central station engineers should cultivate the domestic load, the author realizes that there are many difficulties to be overcome; he is of the opinion, however, that the examples and curves shown are sufficiently attractive to encourage one at least to give the business a trial. The mere fact that difficulties are present invites investigation, and is it not correct, that almost every "worth while" object is reached by overcoming difficulties? There are thousands of pounds' worth of business to be secured in almost every district. The public are in a receptive attitude towards electrical appliances, and there are three essentials to enable this harvest to be reaped:

(1) The will to do;

(2) Absolute belief in the commodity; and

(3) Adequate support for the campaign by the giving of sound service.

While the paper has dealt mainly with the electric supply aspect, the principles are applicable to either manufacturers or contractors, and contributions to the discussion by the latter will be extremely valuable.

In conclusion the author would like to express his thanks and appreciation to Mr. W. F. T. Pinkney of the Newcastle-upon-Tyne Electric Supply Company for his valuable assistance in supplying the figures relating to Billingham and for the loan of the ammeter chart from which the week's curves were plotted.

## Discussion before The Institution, 30 November, 1922.

**Mr. L. L. Robinson:** Those of us who are really anxious to sell "service" to the public from our supply of electricity must feel greatly indebted to the author for reading his paper at this most opportune moment. The public mind, which has heard so much of "therms," was never better tuned for the reception of the all-electric domestic message. There must be an abundant demand for the supply of electricity before it can be cheap and plentiful. The best way to make it abundant is to sell as much as possible to each consumer: make each service do its utmost. Do not let the consumer be satisfied to use only that which can never be sold to him cheaply, namely light, but see that it pays him to use electricity for every possible domestic service. In my opinion the most important information disclosed in the paper is the Billingham load curve and the deductions made from it, with which I concur. Unfortunately we have not only to convince the public that we wish to give them something worth having in the shape of electrical home labour-aids; we have also to convince our colleagues that they can do the same at apparently a very small price per unit and at the same time do good business for the undertakings for which they are responsible. The Billingham load curve must tend to dissipate their fears that cheap units will cause their plant and mains to be overloaded. The curve proves conclusively, at any rate for that case, that the domestic load will not materially affect the peak demand. That is the conclusion about which I have long been convinced, perhaps imaginatively rather than by scientific measurement. To create new business one must have imagination to enable one to look ahead. Do the job and examine its scientific aspects afterwards. However, blocks of all-electric houses are now being connected to my mains and these will enable me to collect data which, I anticipate, will confirm the Billingham data and show that the characteristics of the south are akin to those of the north. With regard to tariffs, I realize that the perfect tariff must be arrived at by evolution. The two-part tariffs in use to-day are tending in the right direction, but the unit rates are too high for the all-electric home service, including heating and hot water, though quite low enough for mere cooking to pay the consumer to use electricity. This is because the majority of consumers to-day are not electrical "whole-hoggers" and they are offered a rate which suits the faint-hearted best. I believe for the moment in a multiplicity of tariffs, each simple in itself, to give the consumers something to choose from, always provided that the flat rates are not so low that certain consumers are supplied at a loss; but I think the ideal tariff for the "whole-hoggers" could be worked out on lines which were suggested to me in a recent conversation with Mr. A. F. Berry. In consideration of the consumer agreeing to use not more than one gas boiling-ring and not more than one coal fire, and to use gas, liquid and solid fuel for no other purpose in the service of his house, the following rates will be charged: A rent per kilowatt per annum, say £*x*, the consumer's maximum demand being restricted by a limiter which will interfere with the supply when the agreed demand is exceeded, and a unit rate only fractionally above the undertaking's fuel cost per unit sold, say $\frac{1}{4}$d. to $\frac{1}{2}$d. per unit. It is difficult to decide exactly what the charge per kilowatt should be. The actual demand at the worst may be made up of, say, $\frac{1}{2}$ kW of lighting load, with practically no diversity, and $4\frac{1}{2}$ kW or more of cooking load, etc., which may have a diversity of 6 to 9. With such a service the size and design of the consumer's installation would be unlimited. He would have one price for current for all purposes, and he could keep within his stipulated demand by switching off something he did not want at the moment, such as a fire, sewing machine, vacuum cleaner, etc., and unnecessary lights when the cooker was on. All night, and at many other times when nothing else was being done, he could divert his power to the hot-water storage tank, so that he could dispense with gas and solid and liquid fuel, together with all the dirt and inconvenience that those antiquated household commodities bring into the house. It is surprising how much coal and gas cost in an ordinary middle-class house. Generally this saving alone will be more than sufficient to pay the electricity undertaking's kilowatt rent, and the unit bill at $\frac{1}{4}$d. to $\frac{1}{2}$d. will be small for all the advantages which are obtained in the all-electric home. If a consumer must have a coal fire, let him have it and pay for it as the luxury item, regarding electricity as the necessity.

**Mr. A. F. Berry:** The lines on which Mr. Robinson has spoken suggested themselves to me when considering the big water-power schemes in America, New Zealand, etc. There are the capital charges, and there is a class of customer who wishes to pay for what he uses, and not a penny more, and therefore it has always seemed to me that the first step to take is to engage a representative to carry out propaganda work on behalf of a full electrical service. If this representative points out that the *total* bill as well as the coal and gas bills will be greatly decreased if the consumer adopts electricity almost exclusively, I have no doubt that the consumer will be willing to adopt electrical service. I have sometimes been asked by appreciative consumers who have had electric installations in their houses for some months, why they had not been approached before. In conclusion, I submit that it is in the power of the electrical industry to pay such salaries as will attract the kind of man who will form a valuable connecting link between the supply undertaking and the consumer.

**Mr. J. W. Beauchamp:** The electrification of the home has become a subject of such importance that I suggest we can regard it as being properly within the scope of the Institution work. The physical characteristics of the supply of heat, light and power to thousands of homes will have an important bearing on the development of power stations and supply networks, and will be as worthy of careful study as many other questions which have been considered here. Obviously the author's principal object is to draw attention to the diversity of the domestic load; his charts and information make the paper most valuable. We have to convince supply engineers that the load has, and as it grows will continue to have, the important characteristics revealed in the paper. In many cases fear exists that to cultivate domestic business in a large way at rates which will satisfy the public may entail loss owing to great additional investment being required. It is necessary to show that this is not the case, and figures which I have received bear out those put forward by the author. It should be noted that the curves in the paper refer to a group of 25 houses. We have had many from single houses, but these group results are important and more of them will be welcomed. In advocating the electric method of cookery we should do well to maintain that valuable feature of the electric cooker as we know it, the independence of the various working items. We can encourage the public gradually to discard the idea of centralized cooking as practised on the coal range, a heavy apparatus doing a variety of jobs and one in which heat losses are immense if only a portion of the fuel duty is required to be performed. It is noticeable that in American practice there has been great development in the use of small cooking apparatus, e.g. grills, light ovens and other appliances. This method must secure a very high diversity of demand. The customer's investment on apparatus may be greater than where a range is used and everything is done in the kitchen in a centralized way, but although the units per kilowatt of connected apparatus are probably lower, the units per kilowatt on the peak are no doubt greater than with more centralized methods. On page 198 the author mentions that at 1½d. per unit all cooking in a certain establishment is done for 5s. a week; he could deduct from this two to three tons of coal a year, when the additional charge for cooking the food in the electric way would be some 4d. or 5d. a day. I should like to point out that the average cook-general costs, in wages alone, 34d. a day; an addition of 12 per cent to that covers the cost incurred by using electricity in place of coal for cookery, a small increase for the improved service, greater comfort and cleanliness and the help which that method in the kitchen gives to the whole of a household relying upon one servant or upon the unaided efforts of the mistress.

**Mr. W. R. Cooper:** I suggest that all propaganda work such as is mentioned in the paper should be undertaken by women and not by men. Women are very conservative, and they can be converted to new methods much more readily by other women who are in a position to appreciate difficulties that are not apparent to men.

**Mr. W. R. Rawlings:** The author has, I think, shown that current can be produced at a low price, and there are plenty of manufacturers able to provide the apparatus, but it is the public who wants both, and neither the supply station engineer nor the manufacturer is in a proper position to deliver his goods to the consumer; the contractor is the man who should be called upon to carry out that part of the business. The author, however, suggests the employment of a staff of representatives to tour the country and effect sales. I maintain that what is needed is co-operation between the supply station engineer, the manufacturer and the contractor. If this is obtained the industry will progress very much faster than it is doing at present. Many contractors have sunk large sums of money in showrooms, without any assistance from the supply undertakings, who should assist by giving a rebate to foster exhibitions of apparatus. Although the supply engineer is quite willing to put down large sums of money for advertisements, he will not, for some unknown reason, give the contractor proper assistance. Contractors as a body are anxious to combine in tackling this most important subject of bringing home to the public the advantages of using electricity for purposes other than lighting.

**Mr. A. C. Cramb:** In the paper the necessity of the sales staff taking electrical apparatus into their own homes and gaining experience with them is referred to. It is, however, difficult to convince the electricity supply undertaking on the point, and although the station engineer may be in some cases blind to the possibility of developing this side of his business, in many cases he is severely handicapped in this way. The author puts forward a suggestion for tariffs on lines recently adopted by the Croydon Corporation electricity works. We came to the conclusion that the average amount paid per consumer for lighting was about 15 per cent of the rateable value of his house. We were at first in doubt as to whether to adopt as a basis the rateable value or the amount of floor space, but we eventually decided to adopt the former as being more reliable. In the case of business premises we took the number of kilowatts of installed lighting capacity and found that this worked out at about £16 per kilowatt. We instituted these alternative rates with a running charge of 1½d. These systems were put into operation at the end of the summer, but the response was very small indeed. I am convinced that the two-rate tariff is the correct method of charging, but I am equally convinced of the difficulty of demonstrating its advantages. I find from experience that if the advantages can be explained to the consumer, say a shopkeeper,—that he can switch on his lights at any time of the day if it is dull, that it will only cost him 1½d. instead of 7d. or 8d. and that he can leave the lights on during the evening—he will adopt this tariff. Many supply companies, both private and municipal, make practically no effort to advertise electricity and put forward its advantages, and it is astonishing that so little effort is made in this direction. I should like to say a few words in regard to the Electrical Contractors' Association, referred to by Mr. Rawlings. A large number of undertakings in this country are now only allowed to hire out apparatus; they are not allowed to sell it outright or on the hire-purchase system, and the Electrical Contractors' Association is responsible for that state of affairs. I put it to them that it is necessary for them to co-operate with the supply undertakings and to justify the position they have taken up. I am convinced that the present position is a great handicap to the development of electricity, and I hope that the Electrical Contractors' Association, which I believe is now in a strong position, will take up this question of co-operation with supply undertakings. In one district in the United States, approximating in size to Croydon, the supply undertaking has just completed a month's propaganda for the sale of domestic washing machines, with the result that 250 have been sold. If that can be done in America by a supply undertaking, surely electrical contractors should be able to do much the same in similar areas in this country. Unless the Electrical Contractors' Association advise all the contractors in an area to work together and co-operate with the supply company, it is impossible to make much progress. I hope there will be a great deal more done in this direction, and I am anxious to help in every possible way. What the author says in regard to the effect of the cooking load on capital cost affects this matter indirectly. We find in a residential district, where the length of the mains is a serious item, that in the case of three-wire cables the size of the middle wire will certainly have to be increased. With a lighting load the consumers can be balanced on the two sides of the system, but that cannot be done with electric cookers unless the distributors are large. The cooking load will be very big, and it will lead to a great deal of trouble. We have, however, experienced many difficulties in developing lighting and power, and there is no reason why we should not overcome the cooking difficulties in the same way as we did the others.

**Mr. A. N. Rye:** My remarks will refer to the point of view of the smaller undertakings. As Mr. Cramb mentioned, we have experienced trouble with the middle wire, but that is a technical point, and I do not want to deal with that at the moment. We do not attempt to encourage the use of the larger apparatus. The real point is that the smaller undertakings cannot afford sufficiently attractive rates, and it seems to me that those who cannot afford attractive rates should concentrate on smaller apparatus. In a number of small companies with which I am associated, 8 000 pieces of small apparatus * have been connected in under four years, which is conclusive evidence that electricity is extremely popular with the consumer. That has been done on rates which are frankly not cooking rates at all, but very much higher than those which have been mentioned, yet I believe that everybody is satisfied. There is quite a large field in domestic load on a small scale for small undertakings. We have also tried hiring, but without much success, so far as our group of companies is concerned. We sunk about £3 000 000 in hired installations and apparatus, but a very high rental is required to cover depreciation and obsolescence, and the consumer will not pay the figure of 20 per cent mentioned in the paper. We have also tried the two-part tariff and found it very effective. In one undertaking 65 per cent of the revenue from users other than power consumers is derived from the two-part tariff, and only the balance from a flat rate, which I think is proof that the two-part tariff can be developed by enterprise. I am of the opinion that the smaller companies must wait for the larger ones to lead the way in regard to large apparatus, and then, if the results are sufficiently good, it will be time for the small undertakings to consider whether they will relay their mains, an operation which in most cases will be necessary. Under present conditions a small undertaking cannot cater for large apparatus unless a supply in bulk is available and the distribution is by alternating current so arranged that large consumers can be supplied from the high-tension main through their own transformers.

**Mr. W. J. Thorrowgood :** One speaker has mentioned the figure of £72 as the probable total cost of electricity for all purposes per annum, per house, but those who can afford to pay this price are few. If the use of electricity for lighting, heating and cooking is to be encouraged, it is necessary to find out what the consumer needs and meet his wishes, including the cost. It seems to me that there is a mine of wealth for supply companies in the smaller houses of the community, and if electricity were supplied to such houses a great deal of good would be done. If the tariff be reduced to, say, ½d. per unit, the resultant load will necessitate a great many super-stations all over the country.

**Mr. P. M. Baker :** In my opinion the propaganda which is of most importance is that which touches the consumer's pocket. It must be remembered that it is far from easy for the central station engineer to deliver heat units, produced by the combustion of fuel in a generating station, at a price which will compete with the direct production of heat in a coal range of good design, used in as efficient a manner as possible. When coal (or even gas) cooking devices are installed the advantages must be very real if the householder is to be induced to displace them in favour of electrical appliances. Even when installed, the full advantage of the use of cooking devices may not be realized, as servants do not always use them carefully or efficiently. The cook who is accustomed to the coal fire and knows that she has to light it some time beforehand in order to cook a joint, may treat the electric cooker in the same way, or she may forget to switch off when the job is done, thus not giving the electric cooker a chance. The all-electric house is a very attractive idea, but the lack of standardization of plugs and sockets and the difficulty of getting replacement parts for burnt-out apparatus are serious disadvantages which call for attention.

(*Communicated*) : The difficulties mentioned above were founded on personal experience. As, however, my remarks were kept as brief as possible and may therefore have been misunderstood, it seems desirable to amplify them slightly. It follows from the first part —that dealing with cost—that the supply authority which undertakes a cooking load must : (*a*) aim at the highest possible generating and distributing efficiency ; (*b*) offer power on a carefully worked-out tariff ; and (*c*) adopt some scheme, such as hiring, which will relieve the householder from the capital cost of installing appliances that will be of no service to him when he removes to another area where the voltage is different. In many areas supply engineers have taken these steps and are meeting with considerable success, but such conditions are by no means universal. The advantages and disadvantages depend on the circumstances of each special case ; thus, the most difficult householder to convert is probably the one whose kitchen range has to be kept going all day long for heating purposes. I do not think that my views are at variance with those of the author, and I put them forward in order that he may indicate how he would meet the difficulties which I have raised.

**Mr. H. T. Young :** Much has been said on the development of the domestic load and I hope that, now the Institution has interested itself in the matter, some action will be taken. The gas companies are at present carrying out much propaganda among doctors and architects, the latter for the reason that people are just beginning to change houses again in a general way. There is no doubt that it would pay us to give professional men current and service at low prices ; money spent in that direction would be well invested and we should save it over and over again in our advertising propaganda. How can we get the men in our own industry to use electricity for all purposes ? Many electrical engineers are using gas, and the gas companies can prove it to the prospective electrical consumer. We must pay attention to that point. An enterprising manufacturing firm has recently made the suggestion that we should do something to get the men in our own industry to use electric cookers, by reducing the price of such apparatus to them. Electrical contractors will no doubt be pleased to carry out the installations more cheaply, or possibly at cost price, and if the supply companies will let them have the mains run into their houses without charge something can be done. I think it would be an advantage if the supply companies would generally adopt some multi-part tariff or contract rate. Thirty years ago few houses were wired for electric lighting. Many of those houses have since been occupied by six or seven different families, and the installations have been so altered that they are of no use to-day. New tenants often require structural alterations to be carried out, and frequently the houses have to be rewired. That is the time to put in a heating installation. Often we are told that the expense is too great, but a plug in each room for the heating appliance, and one main cable and one meter would be a great advantage on a contract rate. I feel that co-operation immediately between manufacturers, contractors and electric supply undertakings will be profitable to all concerned.

---

* The apparatus connected from January, 1919, to October, 1922, included the following: Fires, 2 400; irons, 2 531; kettles, 566; boiling rings, 340; vacuum cleaners, 296; fans, 200; toasters, 208; ovens, stoves and cookers, 101; grills, 57; coffee- and teapots, 44; hot-plates, 42; milk- and water-heaters, 29; egg-boilers and saucepans, 34; sundry, 121.

[Mr. Gillott's reply to this discussion will be found on page 216.]

## North-Eastern Centre, at Newcastle, 27 November, 1922.

**Mr. W. F. T. Pinkney:** We have long recognized in Newcastle that the domestic load is a promising one, but we have not pushed it with the utmost vigour until recently, as we were more or less standing alone in past years, and had no very clear idea at first of the effect of the load on our mains, etc. We knew also that cookers would be greatly improved in design, and in the early days consumers for domestic electricity were rather hard to obtain. Consequently, the selling of domestic electricity was relatively costly. Domestic users, however, if hard to obtain, were at least easy to retain. The position is now changed. We know fairly accurately what is the demand which the load makes upon distribution; in addition, apparatus is improved, and consumers are easy both to obtain and retain. The author's figure of 300 units per annum per kW installed for cooking is rather on the high side for an average figure. Improvements in cooker design should have the effect of increasing the average consumption rather than of still further reducing it, as there is still a tendency to use the electric cooker as an auxiliary to a coal range, and improved design will increase the use of the former and decrease the use of the latter. The author's suggested principle of tariff-making is quite correct, but he has omitted to point out that the great advantage of a two-part tariff to the supply authority is that the fixed charge provides for a minimum annual revenue, whereas the minimum charges provided by statute are generally quite inadequate to meet the costs of availability of supply. I will show a further curve illustrating the demands on another all-electric village where the occupants are not in any way associated with the electrical industry, are of the working class, and have no special concession with regard to tariff, and the demands and consumption follow those of the Billingham village very closely indeed. When the domestic load is built up there will be greatly increased demands for large generators, cables, transformers, switchgear, protective devices, meters, wiring and accessories. In fact, it means an enlargement of the industry. Every individual member in the industry ought therefore to interest himself in domestic electrification, and we who are doing all we can to promote it find unfortunately a great deal of lethargy displayed within the industry, and there are many cases in this district of important electrical officials using electricity for lighting, but using coal, gas and any other alternative for other domestic purposes. It would almost appear as if men were deliberately retarding the wheels of progress within their own industry. It is clear, therefore, although it may seem absurd, that much of the propaganda work has yet to be done amongst electrical men. The author's skeleton plan of campaign follows very closely the lines adopted in this area. He points out the advantage of a proposed financing company in London to assist supply authorities: there is and for many years has been a similar company in Newcastle.

**Mr. W. Cross:** During the past few months, thanks largely to the propaganda work of the Electrical Development Association, more attention has been paid to the selling side of our industry which, in the past, has been somewhat neglected by most engineers, though it is probably equally as important as technical matters. The figure of 300 units per annum for each kW installed for cooking, given by the author, does not seem to agree with the formula previously published, i.e. I unit per person per day. Assuming that a 4 kW oven is employed with a family of 5 people, I 200 units will be used according to the new formula, and 1 825 units according to the old. I should be interested to know the total consumption of units per house per annum at Billingham, and also what current is used during the night. The tariff suggested by the author appears to be a fair one. If the heating load increases, however, a capital charge will surely be incurred through the need for additional copper in the mains and extra plant which will have to be taken into account in forming the tariff. It is, however, desirable to keep the cost of current as low as possible for heating, even if the cost of current for lighting is higher. I do not find the labour-saving argument to be very helpful, as women are conservative and, unless they do their own work, do not worry over efficiency (as understood by engineers): probably if men investigated matters, as suggested by the author, the labour-saving argument would lead to greater results. The author infers that the larger proportion of the actual propaganda work shall be carried out by the supply authorities; I certainly agree that they should bear the greater proportion of the cost, as probably 75 per cent of the profit arises from the sale of current, but I think that they could co-operate more fully than in the past with contractors and retailers, who act as unpaid canvassers for the sale of current and are frequently in closer touch with the consumers. I consider it essential that any scheme of selling should be arranged mutually (or that the supply authority should at least let the contractor know its plans) so that similar statements and arguments may be used to the consumer. Sometimes unwittingly, contradictory statements are made which prevent a sale being completed, and by combined effort more business may be obtained for everybody. I believe that continuous demonstrations in a permanent model house would lead to increased business, and would not in the end be much more expensive than spasmodic efforts lasting a short time in various houses; this should be undertaken by the supply authority as an advertisement for the sale of current, as only one efficient demonstration would be profitable in any but the largest towns. It may be necessary to hire cookers or other devices costing over £10 at present, but I do not think it is desirable or necessary to let on hire cheaper articles, such as irons, kettles or fires. In selling cookers, one is usually met with the question of the provision of hot water which is usually supplied from the cooking range. I should be glad if the author would state where full information can be obtained regarding the alterations needed (and the cost of the same) to enable the kitchen fire to be dispensed with. A pamphlet on this subject showing details of various suggestions would be of great interest.

**Mr. P. F. Allan:** As one of those who endeavoured to introduce domestic electric cooking and heating in the early days (about 1908–10), I have lively recollections of the difficulty caused by the first high cost of the apparatus, and the subsequent frequent and costly renewals of elements, etc. It is gratifying to know that we are now to some extent overcoming both of these difficulties. No electrical engineer who has considered the question at all carefully can fail to realize the tremendous importance of the possible load, both to the supply authorities and to the manufacturers. Following the precedent of some of the electrical Press, Mr. Pinkney has complained of the fact that some electrical engineers have failed to use electrical apparatus. There is, however, something to be said on the other side. Assuming in the first place that the electrical engineer in question is able to get a house in a district where electric supply is available, he soon begins to realize why electric cooking and heating have not made more headway in this country. The prices charged for current in the majority of cases make any but occasional heating by electrical methods an impossibility for a man of moderate means. Cooking is not handicapped to the same extent, but if on an old system our electrical consumer may find, as I recently did, that the amount of load to which he is limited makes the installation of suitable apparatus impossible. In my particular case I have used electric cooking and heating apparatus wherever possible since 1908, and yet in a district supplied by Mr. Pinkney's company, and where in any case gas apparatus has to be bought outright and is not supplied on hire, I have been forced to install gas for cooking in place of electricity. I fear that, even nowadays, very few supply authorities consider it necessary to encourage their own staff to use electrical apparatus by helping them either with wiring or the supply of apparatus. In the early days to which I have referred there were, I believe, only two authorities in the country who pursued this policy. With regard to the design of cooking apparatus, I am convinced that a great deal more could be done to produce devices in which the benefits of the electrical methods are given their full scope in order to save time and add to the cook's comfort. There is no necessity to follow obsolete gas- and coal-oven practice.

**Mr. W. C. Lambourn:** From the commercial aspect the paper is particularly interesting to the lighting engineer, but none the less to the mains engineer. The latter has his part to play in the attractiveness to the consumer. Progressive municipalities and companies must meet the new demand. This obviously means capital outlay, but inasmuch as the new load promises to yield a return far exceeding the liberally estimated lighting load prior to the advent of domestic load, the outlay will be more than justified. Further, the once idle copper in the daytime will be carrying a load similar to the evening load. Where existing networks are fully loaded, the renewal of mains necessitated will have a two-fold purpose, as it would allow for automatic mains maintenance, which, owing to the age of many networks, would avert probable serious breakdowns and expenditure. I think that this latter course is more desirable than laying separate mains to meet this special load, which would increase the length of mains to be maintained for the one purpose. I think that careful consideration should be given when laying new mains to see that the class adopted lends itself as far as possible to the simplest form of service connection, in order to allow of the least possible cost, thereby making the charge to the prospective consumer a minimum, which, it will be admitted, is a very important item in propaganda work. The design of many networks, allowing for the lowest possible cost of the service cable, makes the charge to the consumer prohibitive, and profitable load is lost. The work of the mains engineer therefore affects the propaganda work considerably, as the invariably first question of the prospective consumer confirms.

**Mr. A. G. Shearer:** It is surprising to find in the paper no reference to the electric heating of water for domestic purposes, as it is obvious that if consumers have to use coal fires for heating water they will naturally use the same fire for cooking. In such cases, all that can be hoped for is that electric cooking will be used as an auxiliary. It has been the common practice for some time to supply electric heaters for domestic water service at rates approximately one-quarter to one-third of the rates for cooking and heating, provided the water-heating load is a flat demand over 24 hours, and usually consists of a heater of a capacity of 500 to 750 watts. Many of the hot-water installations in dwelling houses are not now arranged in the best manner for using small heaters continuously. Supply authorities should study the question of meeting a continuous and steady 24-hour water-heating demand at a rate which would not only be remunerative to themselves but make water-heating an economically desirable proposition to the consumer; such load need not be metered, as a flat rate proportional to the size of heater could be employed. Hot-water cylinders equipped with electric heaters must be efficiently lagged and be of sufficient capacity to enable the necessary heat to be stored in the cylinder overnight, to meet the usual demands of the household during the day. I am of the opinion that, given a lagged cylinder of a capacity of, say, 40 to 45 gallons, the temperature of the water need not be raised above 120° F., and at that temperature the radiation losses would be negligible compared with those of the same heat input to a small cylinder operating at a temperature of 160° F. to 170° F. Until the domestic hot-water supply is satisfactorily catered for by supply authorities, electric cooking cannot be so profitably operated either by the consumer or the supply authority. Although the advantages of electric cooking do not fall short of other methods, the addition of economical water-heating facilities is bound to enhance the advantages of the electric service.

**Mr. P. Ward:** The figure of 300 units per kW installed is fairly accurate, but errs, I think, rather on the high side so far as small households are concerned, for the cooker installed will probably be somewhat larger than is actually necessary for the number of persons catered for. For instance, in a household of, say, 6 persons, a cooker having a total loading of 6–7 kW would be installed and the figure quoted would be about correct. In a household of 4 persons, however, a similar cooker may well be installed, and in such case the consumption will be found to be about 260 units per kW. With regard to diversity factor, the curves in the paper refer to a group of 25 houses. If further groups of 25 were taken there would be found a diversity as between those groups, so that the ultimate factor of a large cooking load would be greater than that for the 25 houses. When connecting a domestic load the question of balance will probably require attention first, and it appears advisable for a record of apparatus connected to all distributors to be kept. In many ways a hiring scheme is desirable. It will be found that the undertaking is better able to keep in touch with a consumer using hired apparatus than with one using owned apparatus. Suppose, for instance, that an oven element fails. If the cooker is hired the hirer will soon advise the undertaking, but if the cooker is owned the repair may be put off from day to day and the housewife or cook, failing to get the good results which we claim she ought to get, will become prejudiced against electric cooking in general. An instance came under my notice within the past few days where a cook was dissatisfied with an oven, and had been so for some time. On getting in touch with the owner he agreed that we should examine it, and some of the elements were found to have failed. These were replaced, the cook is now pleased and the oven, instead of being worn out as the cook thought, is giving good service. We have in this district a large number of cookers out on hire and are sending cookers out at a quicker rate than ever before. The rentals are reasonable and such as consumers are quite ready to pay, despite the fact that they are higher than the rentals of gas cookers. When considering the effect of a cooking demand on the maximum demand of a station, it may be found that the time of the former varies on different networks according to the class of resident in the locality. In cases where more than one network is supplied from one station, this further increases the diversity of the demand on that station, and also the amount of cooking apparatus which can be connected without extra expenditure on plant.

**Mr. F. W. Muncaster:** The subject of the paper is one which is exercising the minds of many engineers at the present time. It is beginning to be realized that consumers' business should be dealt with by specialists, and not by any odd man on the undertaking who may have the time to spare. We may congratulate ourselves on being among the pioneers of active propaganda in this direction. I trust that the paper may bring home the fact that the domestic load has possibilities which are capable of dwarfing power loads in any district. The process will, however, be a gradual one and the new conditions can, in consequence, be met as they develop. The curves and figures relating to Billingham should be taken as being on the liberal side, owing to the fact that the tariff enjoyed by the consumers, who are all on the power company's staff, is not an economic one. Nevertheless, the results are quite satisfactory from a mains point of view. The maximum demand is 11 per cent of the connected load, and the average maximum demand is 8 per cent of the connected load. On another housing scheme with almost identical equipment to the above but supplied under an economic tariff, the maximum demand is 8 per cent, and the average maximum demand is 5 per cent, of the connected load. Referring to the remarks on page 200 under the heading "The Consumers' Gain," I would remark that it is difficult to prove that the electrification of a house, where only one maid is kept, can reduce the domestic labour employed. Electrification does, undoubtedly, lighten labour, but it cannot eliminate the human element entirely. The author suggests the enclosure of leaflets with the quarterly accounts. I would ask him if he has had any experience in this direction, and, if so, what results were obtained. I can hardly conceive that the moment of receiving a bill is a propitious time to suggest to a consumer that he should adopt means to increase it. I am of the opinion that it is worth the extra postage to make the appeal at some other time, and, in order to make the same as effective as possible, to write personal covering letters drawing attention to special points in the advertising matter enclosed. With the remainder of the paper I am in complete agreement and I trust that the outlines of the scheme may be taken up and amplified all over the country. It is only by determined effort that we can hope to make substantial progress, for it must not be forgotten that we have a powerful opposition to combat.

**Mr. T. Carter:** This paper is far more a purely commercial one than a technical one, and I should like to make a few remarks from the point of view of the consumer who, amongst others, is to be the subject of the proposed propaganda. The author says that it is good business to prove to a consumer that his adoption of a domestic or multi-part tariff does not increase his normal lighting account, but if the figures quoted in the paper are to be taken as representative of the average domestic tariff, I fear that it will be difficult to convince me of this. My average consumption shown by my lighting bills during the past two years is about 130 units per annum, and mine is a house where there is about 1 kW of lighting installed. This means that I am using only about 43 per cent of the amount that the author says I ought to be using, and if he proposes to charge me on the basis of his view of my requirements and not on the basis of what I am actually using he will increase my lighting bill out of all recognition, and I shall be found unwilling. The ordinary consumer will object, too, to be told that the cost of wastage or extravagance is so small that it can for practical purposes be neglected; he may rightly tell a supply company advancing that plea that if a cost of 1½d. per unit is negligible for wasted light it is also negligible for useful light, and they had better omit it from his bill altogether if they care so little about it. The great lack of the paper from the point of view of propaganda is that it does not give any simply stated costs of doing things by the use of electricity. A gas company will tell me that I can heat a room at a cost of so much an hour, and I find that their figures are reasonably correct and reliable. Something of the same sort is wanted to convince the non-technical person that it will pay him to put in more electrical appliances than he has had before, and the settlement of the whole affair really rests on a question of the cost of working and the cost of installation. What, for example, do the Billingham consumers pay per annum for the fairly extensive installation that they find in their houses when they go into them? Do they pay at the same rate as I should pay at if I put in the same appliances as they possess? Or have they preferential terms that make it worth their while to use electrical appliances in a way that I could not think of doing? At present, on a rough estimate, I think that I am paying about £20 per annum for my whole consumption of coal, gas and electricity: how much should I expect to pay if I did everything electrically? If convincing data of this sort could be given to those who ask, would there not be a great response? At present we are apt to be told that, being electrical engineers, we ought, for the sake of our industry, to install these things and on the ground of expediency stand any extra cost there may be, but are we, as trained persons, to allow ourselves to be persuaded on those grounds? If the supply companies think it so much worth while to have electrical engineers living in all-electric houses, had they not better come along to us and make it worth our while to give them this advertisement? Surely a good advertisement usually means that the advertising medium receives something for it. We await their proposals.

**Mr. A. W. Crompton:** None of the previous speakers appears to be concerned with the matter as dealt with by me, namely, the supplying of the large and—no doubt as a result of the author's endeavours and the consequent discussion—the rapidly increasing demands for heating and cooking supplies from consumers on networks which were originally laid out for lighting and small power supplies only. One would gather from the paper that, due to the large diversity of cooking, very little increase in the capacity of the mains would normally be required. Referring to the charts on page 199, it would be of interest to know what demands are experienced after 6.30 p.m., as in every case with the exception of Wednesday (when the load reached 12·5 kW) the demand at this time was very little more than that which would be due to the lighting only. I understand that the houses at Billingham have also coal fires and therefore, being small houses where no maid is kept, it would hardly appear likely that much use will be made of the radiators. I am of the opinion that in larger houses the heating would be much more regularly used and therefore the capacity of the mains, having regard to the existing allowable voltage variation according to the Board of Trade Regulations of ± 4 per cent, is soon reached, as heating under such conditions very frequently overlaps the purely lighting peak. It is hoped that further tests and records similar to those shown, but where a bigger proportion of heating is connected, will be made in the near future and thus enable new networks to be laid out or existing ones to be strengthened as economically as possible.

[Mr. Gillott's reply to this discussion will be found on page 216.]

## Liverpool Sub-Centre, at Liverpool, 11 December, 1922.

**Mr. H. Dickinson:** In every trade list and circular many new forms of apparatus are given, thus showing that the manufacturers have made up their minds that there is good business to be done. The author mentions many ways in which the domestic load can be developed and I think we must all agree with the suggestions which he makes. The difficulties facing electric supply undertakings are, I think, two. In the case of a d.c. supply such as we have in Liverpool, where we supply very long distances from our substations, we are bound to find trouble in maintaining the pressure at the ends of the distributors. A big campaign for the development of the use of domestic appliances is of no avail until we have some method of dealing with the load which it will give. We have been considering for some time the best method of putting ourselves in a position to deal with this load, which we hope will in time be a very large one. Where an a.c. system is adopted it is a comparatively easy matter to employ additional substations, but when a new d.c. substation, costing many thousands of pounds, has to be installed, it is a very costly matter. After considering the matter very carefully we decided in the meantime to put in automatically controlled substations, and we hope by this means to handle the domestic load as it grows. If the experiment is not satisfactory and we have to revert to a three-phase system it will entail the scrapping of the whole of the present mains, and we are naturally not anxious to do this. I quite agree with the author that we want a two-part tariff, a fixed rate and a low running cost. It remains to decide what the fixed rate is to be based upon. The rateable value system is not by any means ideal. It has the disadvantage that in the better-class areas in a town the fixed charge bears a higher proportion of the total cost than is the case in the poorer districts, with the result that in the better-class districts the fixed charge will amount to a higher figure than the lighting charge would be on the flat rate, whereas in the poorer districts the fixed charge may be less than the cost for lighting. This difficulty might not be serious if the consumer equipped his house throughout with domestic appliances, but in the early stages where the consumer installs only a small amount of apparatus the position becomes a hardship. If the tariff is based on the kilowatt basis, as the author suggests, it means that the supply undertaking will have to check the number of lights every year to see whether the consumer has added to his installation. If this is not done the consumer may be getting more light at a rate lower than that to which he is entitled. I should like to see some fixed basis adopted which would require the minimum of checking. Has the author ever considered the area occupied by the house or, say, the number of rooms in a house, as a basis? In a scheme of this sort the various types of houses would have to be divided into a number of categories, possibly half a dozen. The author mentions that he does not propose to deal with tariffs, but it would be of great assistance if he would give us any experience he has had, because a simple and satisfactory tariff is badly needed, and if we had that I am quite sure we could get the business. On page 197, the number of units per kilowatt of demand is given as 3 240, but on page 200 another case is given of 290 000 units with a maximum demand of 190 kW, which works out at 1 526 units per kilowatt of maximum demand. If the figure of 360 units installed, given on page 197, is taken and a similar figure for the instance given on page 200, the ratio of the maximum demand to the kilowatts installed is 1 to 3 in one case and 1 to 9 in the other. Can the author explain this? The author refers to the desirability of interesting the ladies in this class of work, and I fully agree with him. I think that if the housewife knew what amount of work she could save, she would do all the canvassing necessary. I think that it is generally appreciated that there is an enormous demand to be catered for, which will take time to secure.

**Mr. J. E. Nelson**: In my view there are two conditions necessary for successful domestic load-building, i.e. cheaper current, and cheap and good appliances. Without this combination I believe that a great deal of time may be devoted to propaganda with very little result. I think that the real problem for the supply engineer is to decide whether the demand, when created, will be a profitable one; if we want it we *must* offer cheaper rates and, if we can afford to do this, the domestic load will build itself without any very elaborate organizing effort being necessary. The best propagandist is a satisfactory service, which cannot be given without reliable appliances. The author has rather concentrated on the cooking side, but I have found that electric heating, while equally profitable to the supplier, is more easily introduced to the home by reason of the relatively cheap apparatus obtainable and its more obvious advantages. When the electric habit is thoroughly established, cooking may become general, but, from the point of view of propaganda work, I believe heating to be a safer recommendation to the domestic electricity user than cooking. However, I do not think that we shall approach the usage common in America unless we can supply the domestic load at much cheaper rates than are usual in this country. Taking the published rates of 10 undertakings in South-West Lancashire and Cheshire, the lowest heating and cooking rate is 1½d. and the highest 4·4d., while the majority are not less than 2d., and at these rates my experience is that electric heating and cooking is a luxury—quite worth paying for by those who can afford it but rather out of reach of the type of consumer for whom the supply authority must cater if it is really to dislodge the gas suppliers and put electric heating and cooking in the same position as electric lighting. The author has estimated 1¼ million units from 500 consumers with a maximum demand of 600 kW on the station, which means a load factor of nearly 25 per cent and, if we can feel assured of this load factor, anything from 0·75d. to 1d. would be a fairly profitable rate. At the lower figure, at least, the rate would need little in the way of external propaganda to recommend it. Under these conditions reliable appliances would sell themselves and help to build up the load. I believe that a low flat-rate is more likely to attract the domestic consumer than even a more favourable two-part tariff which is difficult to explain to the housewife, and I do not care for any two-part tariff which is not based on measured maximum demand. All others if they are successful result in the increased sale of units at a low rate; the low rate may well be offered in an understandable form. The electric iron is a valuable propagandist but many makers spoil an otherwise good job by providing a poor connection for the flexible. Every small electrical trouble tends to shake the confidence of the user in all electrical appliances, and a consumer who has used an iron for 12 months without any trouble is more likely to install cooking and heating apparatus than one who has been bothered with short-circuiting flexibles. Irons, radiators and boiling rings can be purchased fairly cheaply, but the full electric cooker—which comes into direct competition with the very much cheaper gas oven—must, I think, be reduced in price if it is to become an article of general use. The mechanical details in small domestic appliances are frequently faulty, especially at the terminals, and if manufacturers would pay more attention to these points and supply an article less easily damaged and more easily repaired, they would help the supply undertakings to foster the domestic load desired by both. While, under favourable conditions, I see no great difficulty in building the domestic load, the policy of domestic load building by encouraging heating and cooking is not quite so clear, at the present time at any rate. During the past few years the cost of appliances has put the extended domestic use of electricity rather out of court, but even if a spontaneous demand had arisen many supply undertakings have not a suitable distributing system in being to meet increased demands without considerable additions to mains and services, which it would have been foolish to undertake at the prices ruling until recently. This, no doubt, partly accounts for the slow progress made in recent years, but cable costs are now coming down to a figure at which one may hope profitably to increase or extend the mains system to meet additional domestic uses. I think that there are good prospects of increased sales in the domestic field in the near future, especially if the load factor of the supply proves to be anything like that suggested by the author's curves and figures, which will justify the cheaper rates suggested.

**Mr. S. E. Britton:** My house has been completely electrically equipped for more than 10 years, and I am quite satisfied that the results that can be obtained for lighting, cleaning and cooking cannot be obtained by any other means. There are, of course, one or two difficult problems in connection with the supply of electricity for domestic purposes. These are, as mentioned by Mr. Dickinson, distribution and tariffs. I quite agree with the author's point of view regarding showrooms, advertising, exhibitions and other means of giving publicity to the value of electricity in the home. The one unsatisfactory feature of publicity propaganda is that it is extremely difficult to gauge the actual amount of business obtained by such means. Any developments which take place after publicity are naturally attributed to it, whereas it is possible that some of the developments might have taken place without any effort on the part of the undertaking. For that reason I do not believe in spending large sums of money; frequent, inexpensive reminders are probably all that are necessary to achieve the objects in view. On the question of tariffs I quite agree with Mr. Dickinson that it is essential to have a two-part tariff in connection with the supply of electricity for domestic purposes. It does not seem to be very important whether it be a kilowatt charge, a maximum-demand charge, a two-rate meter, a charge based upon the rateable value of the property, or a charge based upon the floor space as in Dundee, for meeting the standing charges, plus a low price per unit. All these methods have their good and bad points, and I do not know of any two-part tariff which is absolutely correct. It becomes a matter of expedience, and so long as a tariff is in use which enables the business to be obtained on a profitable basis, and the consumers are reasonably satisfied with the cost, it is not of great importance which of the foregoing methods is adopted. The diversity factor of 9, referred to on page 197, is a very encouraging achievement. If the author can obtain additional instances to confirm this very high figure, the fear which is frequently expressed in connection with small undertakings as to the inability of their systems of distribution to cope with domestic electricity supply, and the cost of larger mains will soon be forgotten, and every undertaking would soon strive to obtain a substantial domestic load. Another matter which, in my opinion, is an appreciable drag upon the development of domestic electricity supply, is the attitude of the Electrical Contractors' Association. I have not yet been able to see the logic of the Association's attitude towards the selling of electrical apparatus by municipal authorities. In the case of electricity supply companies the Association do not attempt to control the sale of electrical apparatus and the wiring of consumers' premises by such authorities, but as soon as undertakers who are local authorities embark upon such work, the contractors attempt to make themselves heard. They entirely ignore the fact that prior to the supply there are no contractors in many of the towns, and although the undertakers invest large sums of money in promoting the supply they are asked to await the pleasure of others to come along and provide the needs of consumers in the sale of apparatus and the wiring of consumers' premises. Undertakings which submit to this cannot develop as rapidly or be of as great a benefit to the inhabitants of the town as those which do undertake every possible work in the interest of both consumers and undertakers. It is only necessary to observe the achievements of the gas supply industry to realize the extent to which the electrical industry suffers by the refusal of electricity supply undertakings to sell apparatus and carry out wiring work. On the question of hire and hire-purchase, it is very often advantageous to develop the use of a particular piece of apparatus by supplying on hire, but the opportunity should also be given to consumers to obtain the apparatus on hire-purchase or to purchase outright in the first instance. The paper does much to remove the objections which have been raised in the past to the development of domestic electricity supply, and I think it has come at a very opportune moment and at a time when station engineers may anticipate considerable business from the supply of electricity for domestic purposes.

**Mr. O. C. Waygood:** The financial aspect of the problem is what the public will require information about, and propaganda work of the nature outlined in the paper will not, I feel, be very convincing. Let us assume that it is desired to install a 2 kW radiator, and use this to the extent that the drawing-room coal fire could be eliminated. A coal fire of this description would consume 1 cwt. of coal in 60 hours which, with coal at 45s. per ton, would cost approximately 0·5d. per hour. To make the electric fire equal to this in cost of running, energy would have to be supplied at 0·25d. per unit, compared with 2½d. (the figure quoted in the paper). In addition, the maintenance charges due to the elements fusing would have to be met. With regard to cooking, I give below relative figures of the price of electric and gas cookers, and their cost of hire.

| Cooker | List price | Cost of hire per annum |
|---|---|---|
| Electric | £22 | 20 per cent = £4 8s.<br>(See page 202) |
| Gas | £10 | 3 per cent = 6s. |

From this comparison I estimate that with electrical energy at 0·5d. per unit, and gas at 30d. per 1 000 cubic feet, cooking becomes a financial proposition. The author refers to the present tendency to charge 1½d. per unit, but can this figure be taken as an average charge? Experience suggests that the inclusive figure is much higher. These facts must be faced and dealt with in any propaganda programme. Modern examples of huge business enterprise have been built up by catering for the masses, and if the small consumer is to be encouraged to cook and heat by electricity the supply must be available at a reasonable charge. I maintain that if the supply authorities set themselves out to do all in their power to provide electricity at a price comparable with that of gas, the "valleys" of their load curve would soon be filled up. It is necessary to impress upon the minds of the public that the power obtained from electricity is far more conveniently handled than that obtained from gas. Dr. Ferranti once remarked:* "The smoke nuisance in our cities will be abolished as soon as the people realize that a pure atmosphere is worth paying for." But the present cost is too high. If it is impossible to get cheap energy, efficiency with reliability should be the aim of manufacturers of domestic appliances. Several tests have been made in the Laboratories of Applied Electricity of the University of Liverpool in order to arrive at the efficiency of apparatus used for raising water to the boiling point, and it is interesting to note that with the immersion-type heater, under ideal conditions, the efficiency is 90 per cent. The efficiency of the well-known immersion-type element heater averages about 80 per cent under normal conditions. With the standard ring-boiler type of about 0·75 kW capacity, the maximum efficiency was 38 per cent (see Fig. A). These figures show that in order that customers may get the best results, the immersion type is the one that the manufacturers should standardize for kettles. It would be interesting if some further tests could be carried out with a view to obtaining the efficiency of other types of domestic appliances. This is very important and will be more so if the cheap unit is not available. The author's statement that the consumer should be taught to believe that he is only paying 1½d. per unit, whereas in reality he is paying 2½d. per unit, is not good business, and certainly will not encourage it. Let us give the public reliable figures as to what the use of electricity means to them financially, instead of disguising the information or making the figures mean something more than they do.

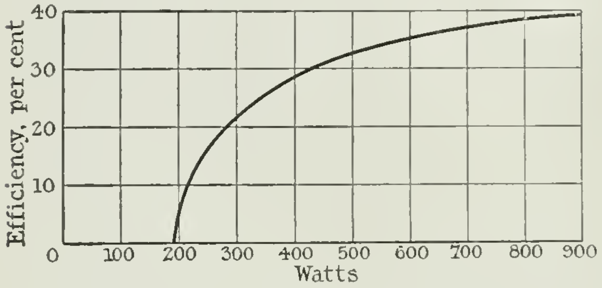


FIG. A.—Efficiency tests on a 0·75 kW flat-ring type boiler, boiling 1·6 pints of water.

**Mr. E. Moxon:** I quite agree with the author that it is absolutely essential that an experienced staff should be available for any campaigns launched, also that this staff should have absolute confidence in the electrical appliances that it is proposed to press for sale or hire, as the case may be. They should have good organizing ability and be tactful, to enable them to deal satisfactorily with the matter. The author gives a figure of 300 units per annum as the average demand in houses for lighting purposes. I am inclined to think that this is somewhat high for large houses, but that it is nearly correct for smaller property. I do not agree with the combined tariff that he mentions, for the following reasons. Take, for example, a consumer having 1 kW of lighting installed and radiators amounting to 10 kW in all (the radiators being used during the winter time only), consuming 300 units per annum for lighting and 1 000 units per annum for heating, and against this take another consumer having 1 kW of lighting installed and a 1 kW radiator used regularly during the summer and winter, and consuming the same number of units for lighting and heating as in the previous case. Although the average cost of current per unit consumed is the same in each case, it will, I think, be admitted that the second consumer is much more profitable to the supply authority than the first; in fact, the author's suggested rate on the combined charge in its present form destroys the object of the maximum-demand system and is little better than a maximum-demand charge for lighting with an independent flat-rate for heating, with the saving grace that it only requires one meter with common wiring for all purposes. I should prefer a similar form of tariff with a fixed charge per kilowatt of maximum demand, having a minimum annual payment against this portion of the rate to cover the standing charges suggested for the lighting installation, together with a low flat-rate per unit consumed, reducing either by a sliding scale or discounts, applying only to a certain consumption per kilowatt of maximum demand, the lower rates to apply successively after calculating progressively the charges due first on the higher rating. Such a tariff would require the addition of a demand indicator to that suggested, but only one meter, whilst the wiring could be common for all purposes. This would give advantage to the consumer with the better load factor and encourage the use of electricity for all purposes, particularly regular heating during the summer months, which in a purely residential town is much desired. With regard to the domestic load on Sundays, the author would, by reference, find that the conditions which he mentions apply chiefly to industrial towns and not to those of a purely residential character. I think that the day will come when electricity will be used for all purposes in preference to coal or gas, and anyone dealing with this subject must take into account the advantages derived from the convenience, handiness and cleanliness obtained when using electrical appliances, as an offset against any slight increase in running costs, whilst the decreased annual expenditure on decorations, carpets, upholstery, etc., will be considerable.

**Mr. A. S. Wilson:** I should like to say a few words from the manufacturers' point of view. Our ultimate goal is, of course, the consumer, and I feel that there is a tremendous field awaiting us for the sale of current and appliances as soon as our combined efforts have impressed on the consumer the efficiency and convenience of domestic electric appliances. This necessitates increased propaganda in respect of the domestic load, and in regard to advertising I consider that the supply authorities can still do a great deal, as the consumers look to them for information rather than to the contractor or the manufacturer. In this connection I feel that much could be done by the supply authorities if their representatives, such as meter readers and inspectors, who regularly visit consumers, were well instructed as to the possibilities of this class of load and were to take all favourable opportunities for pushing this propaganda work amongst the actual consumers. The difficulty of a manufacturer of cooking apparatus in discussing domestic load-building is that it is at once assumed that he is financially interested. This is to some extent true, but at the same time it must be remembered that the manufacturers and sellers of appliances are doing all they can and spending all the money they can afford on exhibitions, fitting up showrooms, etc., and general educational work amongst the public. I consider that this expense should not be confined to any one of those who will benefit by the increased use of electricity for domestic purposes. In other words, the cost of selling to-day, particularly in this line of business, has reached a very high figure and it requires to be spread a little more fairly over those benefiting from the sales of both apparatus and power. The public are beginning to show a keen interest in the benefits arising from the use of electric supply for heating and cooking, and the curves given in the paper appear to show that this load is a paying proposition and also prove conclusively that the load does not coincide with the lighting peak, the fear of which has apparently influenced certain supply authorities against encouraging the development of this load. Another direction in which they might further this cause was suggested at a meeting of the Electrical Development Association in London, i.e. that the supply authority might strongly urge on each new consumer that a reasonable number of power or plug points should be initially installed with a view to the extension of this load, as such advice would be more readily received from the supply authority than from the contractor. There is no doubt that every consumer will eventually use one or more domestic appliances and will then congratulate himself upon having these plug points already installed. The majority of existing installations can already carry two or three times the amount of load at present connected, as there are a number of small appliances such as irons, boiling rings, kettles, vacuum cleaners, etc., which are available and can be operated from existing points now supplying only, say, a 30-watt or 40-watt lamp. These convenient appliances consume, say, 500 to 600 watts and the general extension of their use will almost invariably lead to the adoption of heavier cooking apparatus, provided the supply authorities offer a reasonable tariff and maintenance service to meet the same. From the remarks made in the discussion by representatives of the supply authorities it is very encouraging to note that such a service is being generally considered, and I think that further advantage might be taken of the resources of the Electrical Development Association who are showing a very lively interest in this matter. The lectures being given under their auspices are doing much to bring home to the sellers the amount of work which has yet to be done before we can secure a demand that will justify even one-third of the firms now interested in electrical heating and cooking devices remaining in the business. I consider, however, that the close co-operation of all concerned would result in a tremendous influx of business from this field as soon as the public are made to realize the saving in labour to be derived from the all-electric home.

---

* See *Journal I.E.E.*, 1914, vol. 52, p. 36.

**Mr. R. H. Watson:** From the electrical contractor's point of view the author's suggestions for domestic load-building propaganda are very valuable. The contractor is the best canvasser the supply authority has, as his problem is to persuade people to adopt electricity for every purpose. I should like to offer one or two suggestions with the view to making it easier and cheaper for consumers to install power-consuming devices. In Liverpool the supply authority lays a main into a house to deal with at least 5 kW. Usually the consumer starts with a lighting load only, and the contractor fits service switches, fuses, wiring, etc., for a 10-ampere load, and the supply authority fits a 10-ampere meter. When the consumer wishes to have power for heating or cooking the contractor has to tell him that the service switches must be changed for those rated at 25 amperes. The cost of this change is often more than the actual wiring to the power-consuming point. I think that the supply authority might require a 25-ampere service always to be fitted; if this were done the contractor would gain by not having to stock 5-ampere and 10-ampere fittings, and the supply authority need not stock 5- and 10-ampere meters. The consumer would then be able to obtain his extra wiring at less cost. If the supply main is always installed for a minimum of 25 amperes it would be reasonable for the service switches, etc., to be of the same size. This is, of course, assuming that the charge for current, either for lighting or heating, is a flat rate. The rate for charging is really not within the contractor's province, but from my own experience I would say that a flat rate is desirable, as it is much easier to get the consumer to understand it. I think that, owing to the demand for electricity now being universal, the supply authority does not need to offer separate rates, and that a mean rate could be found for all purposes. In the case of three flats which my firm recently wired, if the consumer's requirements for power and lighting had been met at separate rates it would have necessitated the installation of 8 meters. I think that the author's fixed charge per kilowatt on the two-part tariff is too high. In my own house with an annual consumption of 200 units for lighting, and 200 units for power, at the current flat rates the total cost was only £7 2s. 6d. As regards the author's suggestion of municipal showrooms, contractors would have no objection to this, provided that sales were not effected direct with the public. The showroom should not be run for profit, but should be a charge on the electricity department. One speaker in the discussion expressed surprise that the Electrical Contractors' Association objected to municipalities running showrooms and selling to the public, claiming that the supply undertaking was best able to serve the public. In reply to that I would say that the Association object to municipal trading for the same reason that any other trading sections of the community would object if the municipality started in competition with the ratepayers. In conclusion I think that propaganda work would benefit if the electrical departments of municipalities held occasional informal meetings with the contractors in their districts and discussed propaganda work, as I feel sure they would receive some useful information from contractors.

**Mr. H. P. Tavernor:** I have nothing to add to Mr. Nelson's remarks, but I may say that in my district where the average house has only 10 to 12 lights it would not be advisable to have a two-part tariff. I think that an electric fire, a kettle, and a boiling ring are far better than a cooker in this size of house, and the consumer should be encouraged to add these, and so make up a good power load. In my opinion the ordinary lighting and power rate is by far the best, as the two-rate tariff is too complicated.

**Mr. J. H. Collie:** It seems a very unbusinesslike arrangement to have large power stations which are only loaded to anything like their capacity for a few hours a day, and anything that can be done to encourage a domestic load which will improve these conditions is well worth exploring. I should like to enumerate a few of the difficulties in the way of bringing these appliances into more popular use. In the first place very few supply authorities have been in the position to supply the necessary power, chiefly because when distribution mains were laid they were only of sufficient capacity for what was considered at that time to be the likely maximum lighting load. Consequently, when heating and cooking supplies are taken from them, it generally means that the voltage suffers very considerably. This has been overcome to some extent by the use of a.c. distribution with rotary converters feeding into the low-tension mains. Another very important drawback to the general use of these appliances is the present high rates for electricity. Until authorities reduce the present charges and institute some system of payment based on rating, or charging at power rates all power used above a certain amount, I feel that there will be very little demand for electricity for domestic purposes. Again, most premises require extra wiring for anything above a 500-watt circuit, and this means a fairly heavy initial expense, i.e. from £10 to £20 for even a comparatively small house. Perhaps some arrangement of free wiring or payment by instalments might overcome this difficulty. We are also rather handicapped in this country as compared with America as regards fittings. The standard bayonet lampholder is not nearly so suitable for power connections as the Edison screw type, which will carry anything up to the capacity of the flexible supplying it. Also, the ordinary tumbler switch is not so good as the American type of rotary switch. It is therefore not safe to use on the majority of lighting circuits in this country, appliances which take more than 3 or 4 amperes. It is now, however, possible to obtain bayonet holders and tumbler switches which are a great improvement on the old ones from a current-carrying point of view, and it would be worth while for supply authorities to encourage the use of these types for any installation where smaller domestic articles, such as kettles, boilers and small radiators are likely to be used. If this were done, it would not be necessary always to install separate circuits and plugs.

[Mr. Gillott's reply to this discussion will be found on page 216.]

## North Midland Centre, at Leeds, 19 December, 1922.

**Mr. P. Furness:** The majority of engineers do not, I think, appreciate the domestic side of electricity supply. One of our chief engineers in Yorkshire recently told me that he was very much afraid of accepting domestic load at the present time in view of the fact that the cables in many of the outer districts were on the small side. It appears to me that this paper will do much to dispel such fears. Is the figure of 300 units per kilowatt of lighting installed obtained from a middle-class dwelling? It appears to me to be rather high; I should have thought that 240 units per kilowatt would have been a good average. I agree with the author's opinion that once a consumer is satisfied he tells his friends. In one of our districts where we induced a number of consumers to adopt the residential or two-part tariff this has occurred, with the result that we have now got some 50 per cent of the domestic consumers on that rate. With regard to the question of installing electric heating, cooking and domestic apparatus, I think that the great disadvantage at the present time from the point of view of the medium-class customer is the cost, and the only way of getting this apparatus installed is by some form of hire-purchase. For instance, a consumer is not likely to pay £40 for a washing machine. In our district many people are desirous of putting in all forms of electric heating, cooking and domestic apparatus, and if cheap hire-purchase were available they would do so.

**Mr. H. G. Fraser:** I should like to know if the author has any curves applicable to a residential district. Those given in the paper were of working-class housing schemes, and there would probably be a distinct difference between the two sets. Mr. Furness has said that cables were one of the difficulties in the way of cooking and heating. This is to a certain extent true, although I do not think that one worries much about it. I think the chief drawback in the West Riding of Yorkshire is the difficulty in getting the consumer to buy the necessary apparatus. Even when he has got the apparatus he is very chary about paying for current unless he can get it at a cheap rate. One would imagine that 1½d. per unit is a fairly reasonable rate for cooking and heating, yet it is not easy to sell a large amount of current at that price. I should like to hear other people's experience in this connection. If one could get a reasonable hire-purchase system, combined with a good showroom, one might even get over the difficulty of the unit price, but in a great many municipal undertakings there are difficulties in the way. A large number of us have no selling powers, which is a great drawback, and we also have no wiring powers. I think that if one could go to a consumer and say: "We will put this in for you, we will let you have it on a reasonable hire-purchase system, and we will fit it up, wire it, and send someone to look after it every now and again," one would have a good prospect of doing business, but I do not think that it is sufficient for the consumer to be left to buy the article with as much assistance as possible. In addition, there will, I think, be a great difficulty in selling electricity for cooking purposes unless there is a good hire or hire-purchase system in existence, and unless the undertaker has full powers to carry out the installation and help the consumer throughout.

**Mr. R. E. Gamlen:** I think that in a new district one of the chief questions which people ask is: "How does cooking by electricity compare with gas cooking?" Then they ask: "What shall we have to pay for a gas cooker?" In some places I believe that the gas company will lend a gas cooker free of charge if the consumer agrees to use gas, and when a consumer is told that a charge will be made for an electric cooker he is not pleased. A certain amount of argument is needed before he can be persuaded to see the benefits that accrue from their use. The housewife is easy to deal with, but it is the husband who will decide on the question of cost. Another difficulty is that most people are fairly house-proud, and they feel that the house will be damaged during the installation of the wiring. It is necessary, of course, to tell them that the new system of wiring need not cause any damage. I think that that applies particularly in Yorkshire. Again, if people do not own their house they ask the undertaker to consult the landlord. The landlord refuses to have the wiring done and a deadlock ensues. A good argument to use is to point out that, if they wire their premises, in two years they will probably get their money back, due to the economies to be gained. They have extraordinary ideas of the expense, and have always been told that the cost of wiring is excessive. This is due to the fact that there is no great propaganda in some districts. I think that the best way to get people interested is by means of articles in the newspapers, when small points can be explained. Make a few suggestions as to lighting, the places to put lights and the kind of lights to use. In regard to the question of heating, people do not appear to like an electrical heater in a sitting room. They realize that it is useful in a bedroom or the bathroom, but they like to have a fire which they can poke. I think that the appliances which sell best are irons and small grills. People can generally be persuaded to use a grill, but it is the oven that is the difficulty. A vacuum cleaner, although its usefulness is realized, remains too expensive for the majority. If one could be supplied on the hire-purchase system, or if three or four people were to club together and hire it out, it would be a good plan. The best way to deal with the actual consumer is to try to make an appointment, as he can then choose his time. As to shops, they can be entered at any time, and if the shopkeeper is told that his neighbour has decided to use electricity, he will probably want a supply immediately. It would be a good plan to install in a showroom an ammeter calibrated in pence per hour, so that it can be switched on for exhibition purposes. People will then see what the appliance will cost them.

**Mr. W. A. Toppin:** I am very much in favour of an annual electrical heating and cooking exhibition in any town of importance. When an industry is developing, the more the actual manufacturer is brought into contact with the actual user the better. Without an exhibition how is this to be done? Exhibitions are good advertisements and acquaint electrical engineers in a town with the latest developments. With regard to the curves shown in the paper, I should like the author to say whether electricity was used to the absolute exclusion of coal or gas, for if coal fires were used the load curves might be higher in the summer time owing to the whole of the cooking and heating being done by electricity. If the summer load were higher, then it would be a further argument in favour of supply authorities encouraging this load.

**Mr. S. E. Hall:** Not being directly interested in the supply service, I approach this matter from probably a somewhat different angle. I think that a great deal too much stress is laid on the question of price rather than prejudice, because in my experience the lady in the home is essentially a conservative being, especially in house matters. I take it that the curves in the paper are in connection with houses where there was only electricity available for cooking. I raise that point because I am wondering if the ladies in the houses had the opportunity of using gas or a fire as an alternative. My experience is that the present-day lady who has the latest means available, say electricity, will often use gas, or if she has gas will still use a coal fire. That is prejudice which will have to be overcome. The author says on page 201 that the ladies will "make it their business to persuade their husbands to complete the transaction," but my experience is that it is often the husbands who have to persuade the ladies. I would suggest that either the companies themselves or some syndicate, or some company formed by the contractors should install these appliances in various houses free of charge for a year's trial, without any liability whatever, and of course they will have to follow them up and see that they are used. Sales are not effected very often at the time the canvasser calls. It is the housewife who will get these electrical appliances advertised after she has used them and discussed them with her neighbours. That is when the sales will be effected.

**Mr. W. B. Woodhouse:** The difficulties in the way of developing the domestic load appear to be those which Mr. Furness and Mr. Fraser have pointed out. First of all, it seems necessary that the supply authorities should as far as possible adopt a two-part tariff and make a special effort to get people to use it. The cost of wiring the houses and the first cost of the apparatus are, as far as I can judge, the biggest difficulties in the way. The author has given figures for the village of 282 kW installed and 31 kW demand on the station.

I should like to know the maximum demand for each consumer. As to the benefits of domestic electrical devices, I think that anyone who has used them must appreciate the tremendous saving in domestic labour, and consequently the very great saving in the cost of housekeeping, to which they lead. The paper has helped us to appreciate what a very great field there is for development.

## The Author's Reply to the Discussions at London, Newcastle, Liverpool and Leeds.

**Mr. W. A. Gillott** (*in reply*): I should first thank those who have taken part in the discussions on the paper, for the valuable help and suggestions given. The manner in which the subject has been received at the various Centres proves conclusively the desire of electrical engineers to give the question of domestic load-building much closer study than it has heretofore received. In view of the large number of speakers, I propose to reply to their contributions to the discussion under various headings, instead of individually, as many similar points have been raised by different speakers. By grouping the replies in this manner it enables a more complete answer to be given as a whole. The subjects of tariffs, load curves, distribution and the question as to whether the domestic load is profitable, created the widest discussion, and as these items are so closely bound together I propose to reply to them under one heading.

*Tariffs, load curves, distribution and profitable demand.*—Many speakers have referred to the question of the two-part tariff and have variously suggested that the fixed charge should be assessed upon the rateable value, the rental value, the floor area, the number of rooms, the lighting kW installed, and the maximum-demand system. It would be difficult for me to give a definite reply to these questions, as they are governed so much by local conditions. In some districts where the area of supply is under one rating committee, it may be advantageous to apply the rateable value system, but should it happen that properties of similar size are rated at different values, owing to the districts depreciating or appreciating, it will be difficult to substantiate a difference in the fixed charge where the lighting installations are similar. This may to a certain extent be overcome by a careful system of grading, but it is well known that this difficulty exists in many towns. To apply this system when the undertaking covers a large area—both town and country—would involve many complications in grading. In stable districts, however, this system has much to commend it, as it is a simple basis. Similar remarks apply to the rental system.

The basis of floor area and number of rooms is also definite or stable. Great care is, however, necessary to adjust the amount of floor area to be assessed, as it is open to considerable compromise unless some definite amount, or the number of watts per 100 sq. ft., is established. One consumer's view in regard to adequate illumination will differ from another's. This may to a certain extent be eliminated by omitting landings, lavatories, passages, etc., and I believe that this is practised in some districts.

To assess a fixed charge upon the number of rooms requires a good deal of careful consideration, owing to the wide variation in their sizes. In the better-class districts it will be quite usual to find the large reception rooms with as many as 10 to 20 lamps installed, yet in the same house other rooms may have but one lamp, therefore the necessity arises of grading the rooms. Either of these methods demands a careful survey of the house before the fixed charge is determined, and such surveys are likely to become costly to the undertaking. Once secured, however, they are permanent as long as the property remains the same.

By basing the fixed charge upon the lighting kW installed a nearer approach to the ideal, from a technical aspect, is secured. If a certain margin is allowed when deciding the amount per kW needed to cover capital and other charges, the changing of one or two lamps of a higher capacity will not be a serious item, as the total will be affected to only a very small extent. It must not be overlooked that the available statistics show that 99 per cent of the British public are honest, and the risk of a consumer changing the majority of his lamps after assessment is very small indeed. To check the consumer's installation is no doubt desirable; this can, however, be quite conveniently and cheaply effected when the meters are periodically changed for recalibration.

The maximum-demand system is perhaps the soundest method from the undertaking's point of view, as it automatically regulates the consumer's fixed charge according to his demand. Its greatest difficulty lies in the task of explaining it in a simple manner to the consumer; also, the cost of a demand indicator is an additional item.

The system of charging upon the lampholder basis deserves consideration, as it has the advantage of charging a consumer upon his individual taste or requirements. In establishing this system it should be a condition that electricity is used exclusively for lighting purposes, and a figure that will permit the assessment being based upon a percentage only of the total number of lampholders installed should be determined. For example, if it is found on investigation that the figure necessary to cover capital and other charges is 6s. 9d. per annum per lampholder installed, it is a wise policy to quote 9s. per lampholder per annum upon 75 per cent only of the total number of lampholders installed. This is a good selling point and overcomes the objection of a consumer who is unwilling to pay the same for his lampholder in a cupboard, which is used perhaps a few hours a year, as for his lamp in the rooms in constant use. This method is in operation in Newcastle and Leicester and a similar scheme is adopted in Hackney, but here the fixed charge is based upon a 60-watt lamp. This is a satisfactory system, its principle being to cover the consumer's normal lighting costs by the fixed charge, so that when a low unit charge is added his lighting account is approximately the same as under the flat rate.

The fixed charge also ensures that the undertaking's capital costs are safeguarded, irrespective of whether energy is used throughout the year or not—a sound business policy. From a technical aspect it is immaterial how the fixed charge is assessed, so long as it bears some definite relation to the undertaking's standing charges necessary to cover a lighting supply; this. of course, is a fundamental fact.

The system of charging suggested by Mr. Robinson and Mr. Berry is sound in principle, its object being to induce the consumer to increase his consumption per kW demand by transferring his load to various operations and so produce a high load factor. A similar system to this is, I believe, in operation in Norway, with satisfactory results.

Certain speakers have expressed the need of a 100 per cent load factor at the consumer's premises to justify a low rate. I am of the opinion that if every domestic consumer offered such a demand it would not be a satisfactory condition for the station, as such demand would appear upon the industrial and the lighting peaks and would to a certain degree defeat its object. If really low rates are necessary, they can be effected by encouraging the consumer to use energy during off-peak hours, e.g. during the night, for water heating, etc. A fixed sum per kW per annum can be quoted, a time switch being arranged to operate at determined times to cut out or in as decided. Such a scheme would tend to improve the general load factor of the station, which is of course desirable.

The figure quoted of 300 units per kW of lighting installed has been criticized as being high. Before this figure was decided upon, some 5 000 domestic consumers' accounts, covering different parts of the country, were investigated in order to obtain average results. Such investigations were further subdivided into three sections, viz. (1) Good-class houses; (2) medium-class houses; and (3) artisans' dwellings—using mainly slot meters—and the average annual consumption per kW of lighting installed was found to be, under the various headings: (1) 348 units; (2) 309 units; and (3) 248 units. With such returns the estimated consumption of 300 units per kW of lighting installed is justified. It must be realized that this figure is submitted as a guide to the average return expected, and naturally does not make special provision for "freak" installations. I agree with Mr. Robinson that an ideal tariff is reached by the slow process of evolution, and until we reach that ideal we must work upon sound business averages.

The curves in connection with the Billingham village, no doubt owing to the fact that these are the first set made public, have created considerable interest and prove in no uncertain degree that the domestic cooking and heating load does not present quite so many plant and cable difficulties as most engineers considered. Naturally the low rate offered encourages a wider use of electricity and, as the Billingham load curves indicate, a long-hour use is made, but it must be realized that these tenants do not enjoy a *very* low rate, and that upon the whole they are careful people and do not unnecessarily waste the energy.

In comparing the returns with those of two other housing estates it is of interest to relate that the load-curve characteristic is similar. In one instance where approximately 950 kW of cooking, heating, wash boilers and lighting is installed, the maximum demand was 8 per cent, and the average maximum demand 5 per cent of the total connected load of the village. In the other instance where 1 980 kW of cooking, irons and lighting is installed upon the whole estate, the maximum demand, which also occurs on Sunday, is 100 kW, i.e. approximately 5 per cent. It will be noted that in the cases of Billingham and the 950-kW estate, where each house has a "mixed" load, i.e. cooking, heating, wash boiler and lighting, the percentage maximum demand—10 per cent and 8 per cent, respectively—is higher than that of the third estate, which is only 5 per cent. In the latter case no heating or wash boilers are installed, but it is found upon investigation that although the percentage of demand varies, the return per kW of maximum demand on the station plant is practically identical, i.e. approximately 3 000 units per annum per kW of maximum demand. This must be regarded as a satisfactory figure and one which justifies a comparatively low rate, and it should encourage authorities to seek the load.

Several speakers have asked how the Billingham curves compare with those of better-class residential districts. Unfortunately, at the moment I am unable to submit a curve of this nature, but I hope to do so later. The curves given in my previous paper * represent the return of 13 houses, cooking only, the rateable value of the houses varying from £25 to £60 (pre-war values).

In reply to Mr. Woodhouse, the individual consumer's maximum demand at Billingham varies somewhat, and I have no definite records of all the houses. I understand, however, that it is from 3 to 5 kW.

The question has been raised as to the effect of a general cooking and heating load in a residential district upon a network originally laid for lighting. It is difficult to answer this question accurately, as so much depends upon local conditions. If the cables were laid without much thought for the future it will probably be found necessary to reinforce the network, or it may be possible, as I have found in certain cases (and these can only be decided upon on the spot), to connect quite an appreciable cooking load to a lighting network, owing to the fact of the load being an off-peak load of high diversity. In the case of outlying districts on a d.c. supply, it will probably be found necessary to make some provision for increasing the cable capacity.

The automatic substation mentioned by Mr. Dickinson is a bold experiment, and one which will be watched with interest. The class of district will determine, to a large extent, whether the expense of such a substation is justified. As many speakers have remarked, however, and as the curves prove, the domestic load is a profitable one, can be developed to almost any proportion, and justifies certain expenditure.

With such undertakings as Mr. Rye mentions quite a considerable revenue can be secured by the use of small appliances. These do not affect the cables but, as Mr. Rye points out, they improve the financial results.

*Hire of appliances.*—Reference has been made to the possibility of assisting consumers to use electrical energy by establishing a hiring policy. If any real business is to be done, it is necessary to offer certain appliances upon hire. Places such as Glasgow, Newcastle, Marylebone, Hackney, etc., have proved that the hiring of cookers, for instance, is quite satisfactory. All undertakings now have the power to hire apparatus and it rests entirely with them as to whether they exercise that right. With cooking circuits there does not appear to be any reason why the wiring should not be hired also. This can be run in C.T.S. or similar cable, and is easily removed if necessary. Generally speaking, if ½d. per unit is added, cookers complete with the wiring can be hired without the necessity of a separate hire charge. It is usual, however, for the consumer to pay the cost of wiring and, so long as he is willing to do so, the question of hired cooker wiring does not arise, except in cases of small property which is supplied through a slot meter, so that all charges can be consolidated, as in Hackney, Woolwich, Leicester, etc.

---

* *Journal I.E.E.*, 1915, vol. 53, p. 42.

I would repeat that the supplying of appliances on hire increases the sale of energy. Further, such a transaction with a consumer enables the undertaking to keep in close touch with the installation and this constitutes one of the links of service to the consumer.

*Co-operation in the industry.*—This subject has been raised by many speakers and is of vital importance to the progress of the industry. There are many points of view and I could not effectively deal with them here. Generally speaking, there is a desire for concerted action, and in many centres there are good results, due to a clear, mutual understanding. I am of the opinion that if all parties were to realize thoroughly the fact that the great buying public is, after all, the deciding factor, much good will accrue. The great game of business building is most fascinating and by agreeing upon a definite plan of progress the advantages will be mutual. Each party will, no doubt, secure a greater return by co-operation than by individual action.

*Commercial activity.*—Reference has been made to the extent of an undertaking's activities in regard to propaganda work, i.e. as to whether it should embark upon an extensive scale or proceed in steps. When some new decision is arrived at, such as a reduction in the tariff or the establishment of a hiring policy, I think that such notice should be given a wide publicity either through the local Press or by letter to the consumer. The backs of the account form should, however, certainly be used to convey a suitable message. By making a public announcement the attention of non-consumers is secured and, further, the establishment of a showroom with properly conducted demonstrations will not only attract new consumers but interest the old to make wider use of electricity.

I believe in the principle of spending small sums and often when dealing with one town, and not attempting to interest too many people at once, otherwise proper attention may not be given to inquiries. As Mr. Berry said, it is one thing to have a commodity available, but the most important thing is to present your proposition to the consumer in the right way, and in this respect the representative must be a qualified person, suitably trained in salesmanship. Mr. Muncaster was correct in saying that such work must not be done by an odd man who may have a certain amount of spare time. Electrical undertakings have a valuable commodity to sell and its disposal should be in the hands of good and well-paid men ; it is the cheapest way to get the desired result.

It has been stated that by offering units at a low rate it is not necessary to advertise, as the cheap units will "sell themselves." I cannot agree with this view : it is essential that consumers and prospective consumers must be shown what electricity can do for them, and if the various applications are not brought to their notice, how can one expect them to use electricity ? It may be true that they have some knowledge of the uses of electricity, or where the undertaking is situated, but unless the "desire to use" has been established in their minds very little progress will be made. The old saying "Good wine needs no bush" is no slogan for the present-day business man.

*Miscellaneous.*—Mr. Thorrowgood has remarked upon Mr. Berry's figure of £72 per annum for electricity. Mr. Berry did not intend to convey the idea that this was the figure for the usual house, but quoted it only as an illustration ; there are, of course, many households in which much more than this is spent on lighting, cooking and heating, but upon an average 3 000 units is consumed per annum for all purposes in the average middle-class house of six persons. Using, perhaps, one coal fire, the cost may be anything from £15 to £25 a year. When it is realized that many workmen in humble circumstances are using electricity for all purposes through a slot meter at a cost of from £8 to £12 per annum, it will be appreciated that electricity is not a luxury but a necessity.

I agree with Mr. Baker that the key to progress is economy, but surely electricity offers this. His comparison of the heat units in the coal heap at the electricity works with those in the coal in the householder's range is but one side of the question. In a recent report on "Solid Fuel Ranges" by Professor Barker—a series of careful tests carried out for the Government—it is shown that the kitchen range of good design usefully employs 2 per cent only of the total heat units delivered to it ! It has also been proved that between 70 and 80 per cent of the coal used in a house is consumed in the kitchen range. Now, from an average of some thousands of instances, a middle-class household of six persons using electricity exclusively for cooking, the consumption works out at 40 units per week. The rates of supply differ in many districts, and when making recommendation to a householder one must be governed by local conditions. It is not suggested that where the rates are 2d. per unit and upwards it is cheaper in comparison with coal at, say, 45s. per ton, but where a supply is offered at about 1d. per unit—which is now the case in many districts—one can safely advise the use of electricity for cooking and heating.

Mr. Baker's communicated remarks to a large degree modify his first criticism. The whole object of the paper was to attempt to indicate in a small measure the field open to the supply authority and to point out how the domestic load could be dealt with. His three points are being seriously handled by undertakings generally, especially the first two. The hiring proposition is again being considered, and each week sees an additional authority agreeing to hire appliances.

Mr. Cross requires an explanation of the figure of 300 units per annum per kW installed for cooking, in comparison with the consumption of 1 unit per person per day. In the first case the figure is quoted to the engineer designing tariffs as an estimated figure to expect where a cooker is installed and in normal use. It is perhaps a little low, but it is on the safe side from his point of view. In the second case it is the figure often quoted to the consumer as his approximate cost for cooking when all meals are provided electrically and the appliances are suitable in size to his needs.

The question of converting a kitchen range boiler to electricity is dealt with by heating the water at the cylinder or hot-water storage tank. I believe that there are several of these in use in Newcastle, and no doubt the electric supply company would gladly give Mr. Cross details if he inquired. Almost every maker of cooking and heating appliances will provide a list illustrating these devices.

Mr. Muncaster asks if the quarterly account is a suitable time for introducing new avenues of use. I certainly see no reason why this should not be the case; the backs of the account forms often carry an advertisement suggesting the further use of electricity. The mere fact that the consumer will be forwarding his cheque suggests that he might inquire for something which he saw in the leaflet.

One undertaking which enforced a minimum payment for lighting had difficulty in satisfying consumers as to the reason of such minimum payment. It decided to send suitable leaflets with the accounts, showing how kettles, toasters, etc., could be used from the lampholders. The result was excellent, and they now have but few consumers who use so little energy that the minimum payment is enforced.

Mr. Carter's case is one of the very few where the consumption for lighting is much below normal, i.e. if his load *is* 1 kW. If his total fuel and lighting bill is £20 per annum and he is careful in the use of coal, I am of the opinion that his account would be quite acceptable to him; he is living in a district where electricity is cheap and appliances can be hired at moderate rentals, and I suggest that he, being an electrical engineer, might try electricity for other purposes than lighting. The cost of the specific operations which he mentions will be gladly given by the supply company. It was not the intention of the paper to give such details but to interest the electrical undertakings in the hope that they would do so.

Mr. Dickinson asks for an explanation of the apparent discrepancy between the figure given on page 197 of 3 240 units per kW and the figures on page 200 of 290 000 units per annum. The first set of figures relates to the result of a study of 13 consumers using cookers in private houses; the figure of 3 240 units represents the consumption per annum per kW of demand that falls upon the system peak, whereas the figures on page 200 refer to the consumption for cooking at four restaurant and canteen kitchens, i.e. commercial use, an entirely different proposition. These cases were quoted to indicate that both the domestic and commercial cooking load are worth cultivating.

Mr. Waygood has evidently misunderstood the reference to the suggested rentals. The paper is offered to electric supply authorities with certain suggestions and the statement of 20 per cent per annum upon the *net cost* as a suggested rental of cookers is quite a different matter from the 20 per cent of Mr. Waygood's *list price*. One is the wholesale price which the authority would pay, and the other is the price which the consumer would pay if he bought at a retail shop. The £22 cooker referred to is hired by many authorities at 10s. per quarter, inclusive of all maintenance, and in some districts as low as 5s. per quarter. My figures were quoted as a sound basis to cover interest, capital redemption and maintenance. He also refers to the consumer being misled as to the cost of units; here also is a misunderstanding. The paper distinctly says that he is to pay a fixed charge plus 1½d. per unit, and on this basis his normal lighting account will be practically equivalent. It is the extra units that are costing him 1½d. only, and 1½d. is not the average cost per unit. The various other matters which Mr. Waygood mentions are interesting, but I do not agree with all his conclusions, and as they do not come within the scope of the paper I must ask to be excused from dealing with them.

# THE POSSIBILITIES OF TRANSMISSION BY UNDERGROUND CABLES AT 100 000/150 000 VOLTS.

By A. M. Taylor, Member.

(*Paper first received* 18*th August*, 1921, *and in final form* 16*th October*, 1922; *read before* The Institution 7*th December*, *before the* North-Eastern Centre 11*th December*, *before the* Scottish Centre 12*th December*, *before the* South Midland Centre 13*th December*, *and before the* Sheffield Sub-Centre 20*th December*, 1922; *also before the* Liverpool Sub-Centre 15*th January*, *before the* East Midland Sub-Centre 30*th January*, *and before the* Dundee Sub-Centre 8*th February*, 1923.)

## Summary.

The paper is primarily a plea for the use of single-phase cables. The effect of separating the cores is considered, both in its relation to easing the potential gradient and in relation to eddy currents induced in the lead sheathing.

The gain effected by employing "intersheaths" is pointed out, and the author's proposals for obviating the disadvantages of intersheaths by combining their employment with a six-phase transmission are considered.

An actual transmission of 50 000 kW at 100 000 volts over a distance of 30 miles is worked out in detail and compared with a similar transmission at 30 000 volts. A saving of roughly £500 000 is shown.

The principal conclusions arrived at are:—

(1) Reliability under the six-phase/three-phase system very greatly increased, as compared with plain single-core cables (as at Gennevilliers), or with three-phase cables for equal voltage.

(2) The author's arrangements will permit of loads of poor power factor being taken up, with positive gain in efficiency and regulation.

(3) The maximum voltage gradient being no greater with 100 000 volts than with 30 000 volts, such transmissions can be undertaken immediately the cable makers are in a position to guarantee the cables.

(4) The investment in capital outlay proceeds, in the six-phase/three-phase scheme, in proportion to the development of the load. A start could thus be made with only 8 000 kW.

(5) The reduction in line-charging current in the six-phase/three-phase scheme, and the improvement in "regulation" are very considerable, as compared with those for any other proposals.

## Table of Contents.

I. Introduction.
II. Limitations to the use of three-core cables.
III. The gradings of cables, and potential gradients.
IV. Detailed description of the operation of the six-phase/three-phase system.
V. Certain features of the six-phase/three-phase system (including "regulation" and "charging current").
VI. Reasons for selecting 10 parallel cables for a 30 000-volt scheme.
VII. Conclusions.
Appendix A.—Calculations for a 30 000-volt line.
Appendix B.—Calculations for a 100 000-volt line.
Appendix C.—Further remarks on the question of potential gradients.
Appendix D.—Calculations of electrostatic capacity, charging current, leakage conductance and potential drop on the author's system.
Appendix E.—Relative capital costs of 30 000-volt and 100 000-volt schemes.
Appendix F.—Results of Clark and Shanklin's tests.
Appendix G.—Bibliography.

## I. Introduction.

The efficient and cheap transmission of power electrically over long distances is at present one of the most vital problems connected with the distribution of electricity. The object of the present paper is to consider how this may be carried out in those cases where the use of overhead wires at high voltages (e.g. 100 000 to 150 000 volts) is not considered to be advisable. Doubtless there will be large areas over which the employment of overhead transmission will be permissible, but, on the other hand, the use of duplicate lines of tall towers at comparatively frequent intervals, with spans of heavy cable liable to be brought down during severe snowstorms or other atmospheric disturbances (or liable to malicious interference), could hardly be faced in the vicinity of large towns. There is, moreover, always the possibility that, if underground cables could be employed at voltages of the same order as that of overhead lines, it might be possible to obtain wayleaves over great distances along the existing trunk lines of railways, and in such a case the cost of transmission might be reduced to a figure as low even as that with overhead lines.

## II. Limitations to the Use of Three-core Cables.

The limitations to the use of three-core non-concentric cables are well known, but it may be stated that directly the pressure is raised to 100 000 volts it becomes almost impossible to get the depth of insulation which is needed, both between core and core and between core and earth, within the overall limiting diameter of the lead envelope, which should not appreciably exceed 4 inches.

The recognition of the difficulties thus obtaining in three-core cables has caused many minds to turn to the possibilities of using three single-core cables for three-phase transmission, and such a scheme was proposed by Mr. C. J. Beaver in a paper* read before the Institution in 1914, and has more recently been very fully worked out in a preliminary way by Messrs. Clark and Shanklin of America and presented in the form of a paper before the American Institute of Electrical Engineers.†

From the data given by Clark and Shanklin it is easy to deduce that, with a pressure of 100 000 volts and a frequency of 50 periods, and with unarmoured cables, the lead sheathing being continuously earthed and the cables being not further than 6 inches apart from one another, the loss due to eddy currents in the lead, in a cable of the dimensions shown in Fig. 1, will not exceed 10 per cent of the $I^2R$ loss in the copper alone.

---

* *Journal I.E.E.*, 1915, vol. 53, p. 57.

† *Journal of the American Institute of Electrical Engineers*, 1919, vol. 38, pt. 1, p. 917.

With a 5 per cent copper loss the total loss with unarmoured cables would therefore be increased only from 5 per cent to 5·5 per cent of the total power, i.e. an addition of 0·5 per cent.

It may therefore be taken that, provided single-core cables can be constructed to withstand a pressure of 57 700 volts to earth, both in the cable itself and at the joints, it is allowable thus to separate the phases. The maximum potential gradient in the cable itself can be kept down to that now obtaining in three-core non-concentric cables (about 40 000 V/cm) by simply constructing the copper core with a hempen centre; but the difficulty of jointing is rather more serious.

The author has developed a system on the separated-phase principle which permits of the pressure between the outermost core and earth being reduced to some 18 000 volts while still obtaining 100 000 volts for transmission, coupled with certain other advantages of moment, and it has been thought that a description of this system would be of interest at the present time. In what follows it is to be understood that the amount of power to be transmitted is 50 000 kW, the load factor 40 per cent, and the distance 30 miles.

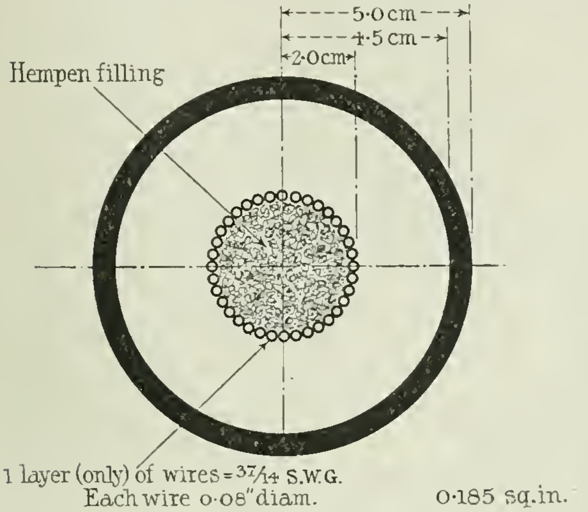


FIG. 1.—Insulation to withstand 57 700 volts to earth.

It is practicable to keep the plain copper voltage-drop (i.e. excluding the lead-sheath loss) over a separated-phase 100 000-volt single-core system down to $2\frac{1}{2}$ per cent of the total power, or 2·75 per cent including lead-sheath loss. On a 30-mile line the lead-sheath loss is thus, at 50 periods, only 0·25 per cent of the total power transmitted.

In Appendix B the author has given certain data with regard to the "cable constants" of a system employing plain single-core unarmoured cables such as shown in Fig. 1 (e.g. capacitance, inductance, resistance, etc.). It may be taken that the figures therein given for the copper voltage-drop, reactance-drop, etc., are not far wrong for the six-phase/three-phase system to be described.

Similarly, the induced current losses in the lead sheathing will also be of the same order, in fact rather less.

It therefore becomes practicable to consider armoured cables, as these might be desirable on long lines laid along railways. By increasing the amount of copper by 10 per cent, the iron-wire loss can probably be compensated for by the reduced copper voltage-drop, and may then be neglected altogether.

In Fig. 2, sections of the various cables experimented on by Clark and Shanklin are given, and also their "Cable C" and, in addition, the cable (marked "No. 11") shown in Fig. 1 of the present paper. The former cable is that on the tests of which the estimated lead-sheath losses herein taken are based.

The sheath diameter of the author's six-phase/three-phase cable is virtually the same as that of the cable shown in Fig. 1. Hence the results for the cable (Cable C) of Fig 2 apply also substantially to the author's system, the location of the average current with regard to the lead sheathing being virtually the same.

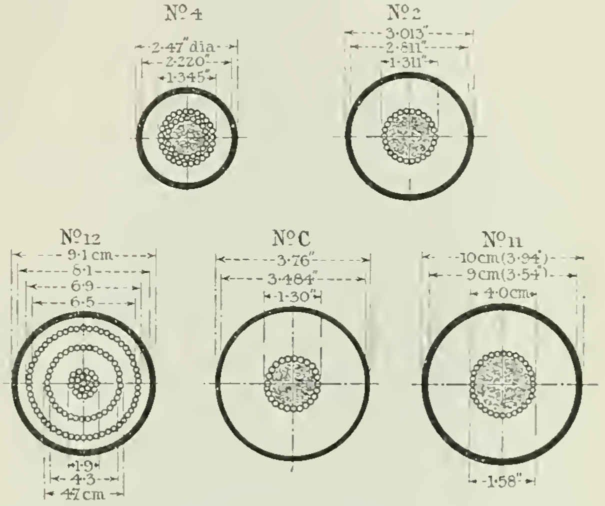


FIG. 2.—Cables experimented on by Clark and Shanklin.

Cable 4: Percentage increase in effective resistance
= 11·4 at 25 ∼ and 96 at 60 ∼; area = 0·79 sq. in.
Cable 2: Percentage increase in effective resistance
= 8·8 at 25 ∼ and 48 at 60 ∼; area = 0·49 sq. in.
Cable C: Percentage increase in effective resistance
= 4·5 at 25 ∼ and 22 at 60 ∼; area = 0·216 sq. in.
Cable 11: Area = 0·185 sq. in.
Cable 12: Cable proposed by the author.

## III. THE GRADING OF CABLES, AND POTENTIAL GRADIENTS.

As the author's system depends for its proper appreciation upon the establishing of certain principles, these will first be investigated and afterwards the system itself will be described.

In Fig. 3 is given a curve ABCD representing the potential gradients of a cable having a core of radius 0·65 cm. The voltage gradients are plotted as ordinates, and the different radii of circular concentric sections of the insulation are plotted as abscissæ. The interior radius of the lead sheath is assumed to be 2·2 cm, and the pressure between the core and the lead sheath is 69 200 volts. The figures given at various points along the curve represent the voltage gradients at those points. The insulation is assumed to be applied in concentric layers, all of material of equal permittivity. Four such circular sections are shown immediately contiguous to the core, and one section at the extreme circumference. The values 8 750, 7 720, 5 700, 4 030, etc., marked between the dimension lines at the foot of the diagram represent the integration of the areas contained in the different portions of the potential gradient curve, and therefore represent potential differences up to the radius of $2\frac{1}{2}$ cm. To be complete, the diagram should of course show the whole 44 of these circular sections, but for the sake of simplicity the remainder are omitted. Each of the equipotential boundary lines separating these circles may be considered to be a metallic sheath of extreme thinness, merely for the purpose of fixing ideas.

If, now, the capacity per foot between any one intersheath and any other intersheath be worked out by means of the formula

$$C = \frac{C_a \cdot k_{(av.)} 2\pi l}{\log_\epsilon (b/a)}$$

where $k_{(av.)}$ = permittivity relative to air = 3·2;
$C_a$ = capacity per cubic centimetre of air = $0 \cdot 08842 \times 10^{-12}$ farad;
$l$ = length in cm = 30·5;
$b$ = outer radius of insulation in cm;
$a$ = inner radius of insulation in cm;

the following values are found:

$$\left.\begin{array}{l} 0 \cdot 000124 \times 10^{-6} \\ 0 \cdot 0001315 \times 10^{-6} \\ 0 \cdot 000185 \times 10^{-6} \\ 0 \cdot 000238 \times 10^{-6} \\ 0 \cdot 001175 \times 10^{-6} \end{array}\right\} \text{farad per foot,}$$

the last figure being for the centimetre depth immediately below the lead sheath. In a similar manner the currents for these successive sections are calculated from the formula

$$i_d = \frac{2\pi f c e}{\sin \theta_d}$$

where $f$ = frequency,
$c$ = capacity per foot length,
$e$ = voltage between core and intersheath,
$\theta_d$ = phase angle of dielectric power factor,

giving the following values:

$$\left.\begin{array}{l} 0 \cdot 341 \times 10^{-3} \\ 0 \cdot 319 \times 10^{-3} \\ 0 \cdot 331 \times 10^{-3} \\ 0 \cdot 302 \times 10^{-3} \\ 0 \cdot 321 \times 10^{-3} \end{array}\right\} \text{ampere per foot of conductor.}$$

It will be noted that the current per foot is constant (within the limits of rough approximation), which means that the capacity current is of the same value

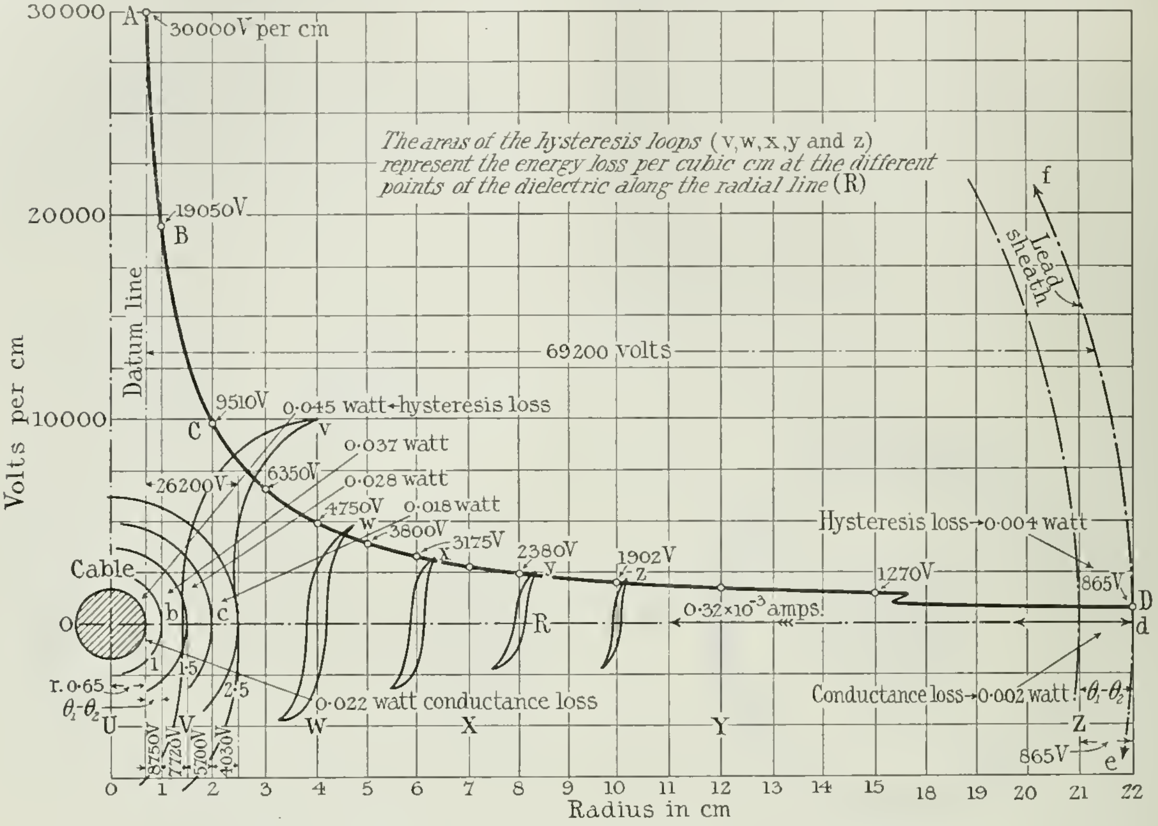


FIG. 3.—Single-core cable; potential gradients at different radii.

in the widely-varying concentric slices of insulation and that the voltage differences across each successive layer vary inversely as the capacity of each layer. Examining the matter further and assuming that the power factor of the dielectric keeps constant throughout the successive layers (which of course is not the case owing to the differing temperatures, but this only makes the author's argument all the stronger), we get the values of the watts lost in each successive layer from the formula

$$w_d = i_d . e . \cos \theta_d$$

which gives us the values shown on Fig. 3, namely

$$\left.\begin{array}{r} 0\cdot045 \\ 0\cdot037 \\ 0\cdot028 \\ 0\cdot018 \\ 0\cdot004 \end{array}\right\} \text{watt per foot.}$$

If the last-mentioned reading had been taken over a ½ cm difference of radius, instead of 1 cm in conformity with the other readings, it would have had the value of only 0·002 watt, which is less than 1/20th of the value obtaining on the slice of insulation immediately next to the core. Now the volume of the slice immediately contiguous to the core is of the order of 1/40th (per unit length of cable) of that at the extreme circumference, and the amount of heat developed is over 20 times, consequently the heat developed per cubic centimetre is of the order of 800 times that generated in the section at the extreme circumference.

In a similar manner it can be shown that the watt loss due to the purely ohmic insulation resistances of the different sections, and to the true leakage current which passes through them, follows a precisely similar law and is, again, 800 times the heat developed per cubic centimetre. This will be seen at once by a comparison of the formulæ for the elastance and the true resistance, to which also may be added the thermal resistance. The three formulæ are of the following relation, viz.

$$R_g = \text{(Insulation resistance)} = \frac{R_g\,\text{(specific)}}{2\pi l} \times \log_\epsilon \frac{b}{a}$$

$$S = \text{(Elastance)} = \frac{S\,\text{(specific)}}{2\pi l} \times \log_\epsilon \frac{b}{a}$$

$$R = \text{(Thermal resistance)} = \frac{R\,\text{(specific)}}{2\pi l} \times \log_\epsilon \frac{b}{a}$$

A little consideration will show that in the case of the first two formulæ the voltage differences follow the above-mentioned law and that the temperature differences will also follow an identical law.

The true conductance losses have also been worked out from the first of the above three formulæ, and the initial and the final values shown in Fig. 3 are 0·022 watt and 0·002 watt. In the particular case considered, therefore, the leakage conductance loss is very nearly equal to the dielectric hysteresis loss, the former being based upon a value for the specific resistivity of 150 × $10^{10}$, which is a value found fairly frequently for the lower temperatures in Messrs. Clark and Shanklin's experiments, and the latter being based upon a constant dielectric power factor of 0·015, which also obtains only at the lower temperature values (up to 72° F.). The author is quite satisfied that the power factor, representing partly as it does the energy lost by dielectric hysteresis, plus the true leakage loss, must be much greater in the inner layers of insulation, which are at a much greater temperature than the outer layers; and, as already mentioned, this would still further strengthen his argument.

Conversely, from the third equation we can see that the greater amount of heat liberated in the sections close to the core has enormously greater difficulty in reaching the circumference of the cable. It therefore follows that any method that tends to relieve the potential gradients in the sections next to the core, even if this occur at the expense of the sections nearer to the circumference, is a very potent factor indeed in easing the situation. In Fig. 4 the author has shown the remarkable effect upon the diameter of the cable of introducing metallic intersheaths and forcing these to work at such potential differences between each consecutive pair that the maximum voltage gradient is maintained more or less constant throughout. The result of this is that the whole of the 69 200 volts is absorbed within a radius of $4\frac{1}{5}$ cm, though it should be mentioned that the diameter of the core itself, in this particular case, has been somewhat increased (owing to inadvertence), and this unduly magnifies the result.

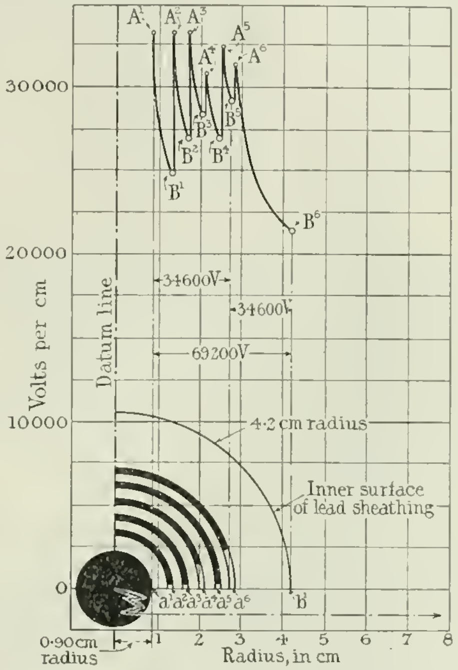


Fig. 4.—Multiple (cylindrical) core cable; potential gradients at the surfaces of the different cores.

A further consideration of Fig. 3 and of the figures given in Appendix C will show that such a result can be obtained only at the expense of having continually increasing capacity currents in successive layers as we work outwards, the current being no longer constant from the centre to the circumference, and practical arrangements for dealing with this have now to be considered.

### INTERSHEATHS.

Fig. 5 may help to fix ideas. This may be considered to be an investigation of what takes place in a single phase of a three-phase system embodying one single-core cable per phase, each such cable having "intersheaths" in accordance with Mr. Beaver's proposals.

The condition considered is that the half-wave of E.M.F. in the secondary is in a downward direction through the secondary winding, "sucking" the principal or "load" current of the central core of the cable and carrying it through to the neutral point of the transformer winding. The various components of the capacity current are shown coming along from the line and finding their way to the central core, as illustrated by the three large arrows 120° apart.

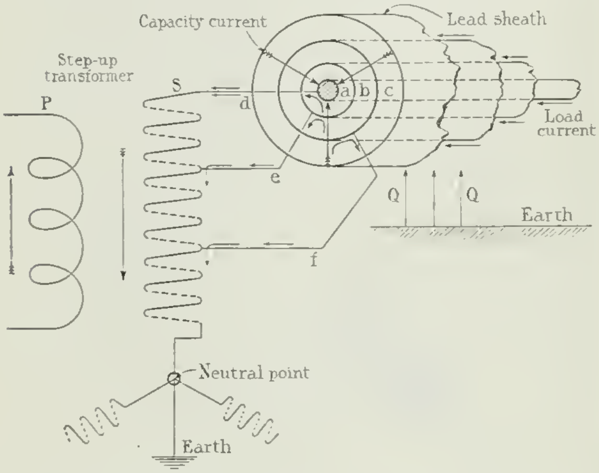


FIG 5.—Diagram to illustrate the relief of the inner layers (capacity and leakage current) by means of intersheaths.

Consider, for instance, the current (f) which arrives through the outermost conducting sheath. Finding a path leading to the tapping of the transformer, the "surplus" current of the outermost section of the insulation, instead of going through the successive layers of insulation to the central core and heating up the innermost layer in the way just described, now takes a short cut across to the tapping of the transformer. The "surplus" element of the current (e), which has passed through the insulation from the outermost sheath to the intermediate sheath, similarly takes a short cut across to the corresponding tapping, with the result that the insulation next to the innermost core is called upon to carry only the capacity current (d) due to its own capacity. Referring again to Fig. 4, it will be understood that, if we had chosen, we could have made the section of insulation next to the core work at a less voltage gradient than 38 000 V/cm, and so have eased the situation as regards this section. The author believes that by adopting the principle indicated above the potential gradient on the outermost layers could be raised considerably higher than would be indicated by Fig. 4. For one reason, these layers being close to the lead sheathing would be the coolest in the whole cable and consequently the power factor of the dielectric would be the lowest and the resistivity by far the highest, since this latter varies enormously with the temperature.

In all probability the operation of dielectric hysteresis is very similar to that of magnetic hysteresis, and the loss (i.e. the power factor where the leakage loss is low) is therefore proportional to a function of the potential gradient, and the loss by pure leakage conductance through the dielectric is proportional to the square of the potential gradient, and both of these (and particularly the latter) depend to a very great degree on the temperature obtaining in the dielectric.

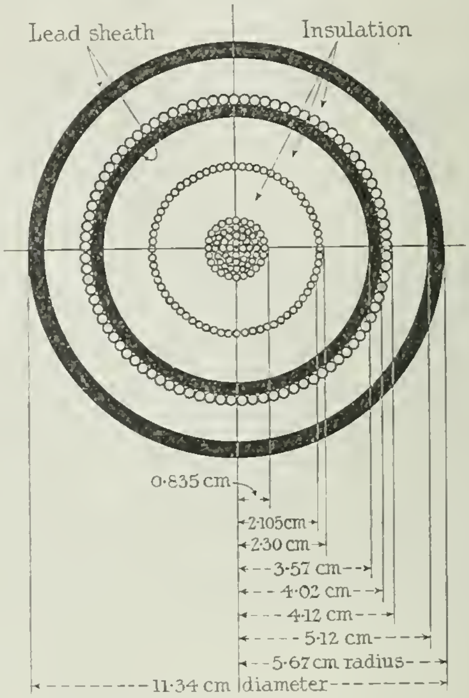


FIG. 6.

The question of the dielectric losses and potential gradients is investigated quantitatively in Appendix C.

## IV. DESCRIPTION OF THE OPERATION OF THE SIX-PHASE/THREE-PHASE SYSTEM.

Referring now to the author's six-phase/three-phase system, which will be briefly described in connection with Figs. 7, 8, 9, 10 and 11, attention is invited to a consideration of one—say the top—of the three small six-phase systems or "hexagons" shown in Fig. 11 (which gives the general scheme) and reproduced by itself in the upper part of Fig. 7. This consists of a "bank" of the secondaries of a step-up transformer coupled in "double star" to give voltages which are in six-phase relation, the vector diagram for which is shown in the upper part of Fig. 8 (right-hand side). This bank of transformers is connected to the two cables shown at the top of Fig. 7, these cables being shown more in detail in Fig. 6.

It will be clear that, if the upper "hexagon" shown at the right-hand side of Fig. 8 be earthed (as shown) at a point having a potential not far different from that of a point midway between the points "e" and "f," instead of at the "natural" neutral point of the hexagon, the potentials of the remaining corners of the "hexagon" with respect to earth will be given by vectors connecting these corners with the said earthed point.

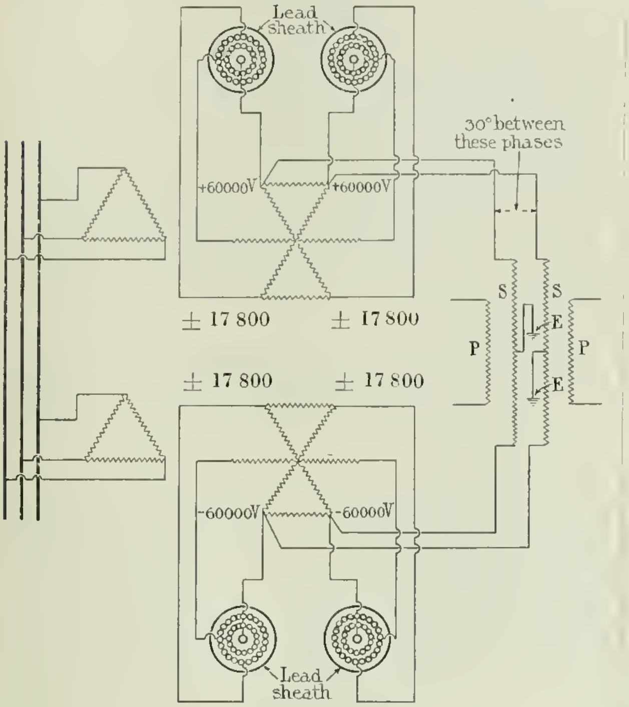


FIG. 7.

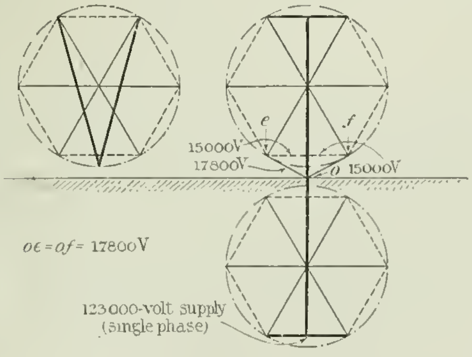


FIG. 8.—Arrangement of combined six-phase and single-phase supply (for railways).

These vectors are not shown in the right-hand top diagram of Fig. 8, but vectors from the two topmost corners to earth are shown in that figure in the left-hand top diagram, in heavy lines, and the positions of the other vectors can easily be obtained.

Both in Figs. 7 and 8 are shown, in the lower half of each figure, arrangements the inverse of those in the upper half, and to the right of the former figure there are shown two single-phase transformers (which may be called the "principal" or "major" transformers) and these are each connected across the points marked "+ 60 000 V" and "− 60 000 V." The secondary of each of these principal transformers is wound for 120 000 volts, and its mid-point is earthed. It may help towards a more ready understanding if these two "major" transformers are replaced, as shown vectorially in Fig. 8, by a single transformer, connected to the two "hexagons," at extreme top and bottom, at points midway between each top and bottom pair of corners of the said "hexagons."

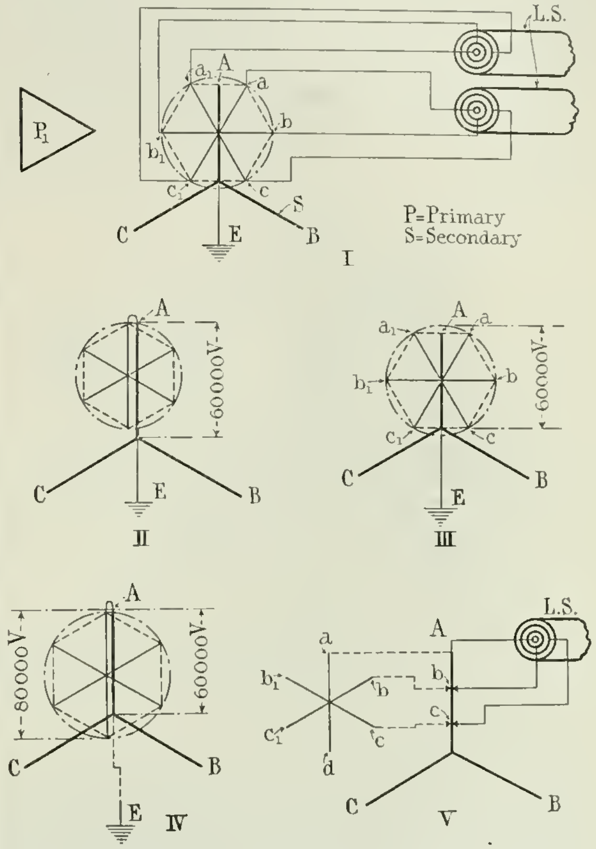


FIG. 9.—In cases I, II, III and IV, hexagons will also be similarly carried by (B) and (C) and two other pairs of concentric cables.

It is demonstrable that, if neither of the two six-phase systems be at any point connected to earth, the potentials of the lower corners of the upper "hexagon," and of the upper corners of the lower "hexagon," will take up the values shown more precisely by the vector diagram in Fig. 8, receiving their potentials from the "major" transformer, through the connections at the extreme top and bottom of the two "hexagons." In this diagram each chord of the hexagon represents 30 000 volts, and this is the voltage obtaining between the innermost core of each cable and the intermediate core, and between the intermediate and outer cores. The voltage between the outer core and the lead sheathing is shown to be only 17 800 volts (if desired, only 15 000).

The cable shown in section in Fig. 6 has been so designed that the maximum voltage gradient on the innermost core under these voltages will not exceed about 38 000 V/cm, i.e. the potential gradient at which three-phase three-core non-concentric cables work at the present day. On the middle and outermost cores it will be 29 000 V/cm and 20 000 V/cm, respectively.

Since the capacitance increases as we work outwards, and since it becomes very desirable (in the case of failure of the lead sheathing or of the outermost insulation) to have as low a voltage as practicable between the outermost conductor and the sheathing—for reasons which will appear later—it will be evident from an inspection of Fig. 8 that the arrangement of the six-phase "hexagons" in the manner shown in Figs. 7 and 8 affords a very nearly ideal way of distributing the potentials.

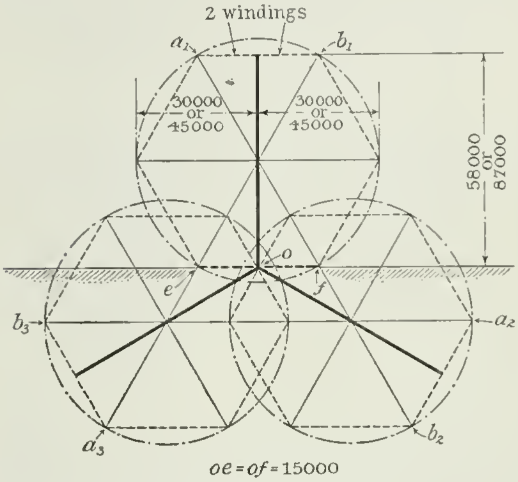


Fig. 10.—Arrangement for minimum stress between outermost core and earth. (*Note:* 58 000 × $\sqrt{3}$ = 101 000, and 87 000 × $\sqrt{3} = 150\,000$.)

Let us now consider Fig. 10. In this case the lower "hexagon" of Fig. 8 is replaced by two "hexagons," and the single-phase "principal" transformer (or its equivalent as in Fig. 7) by a three-phase "principal" or "major" transformer system, the neutral point of which is earthed.

In Fig. 9 are shown various connections of transformers forming the "hexagons," or six-phase systems, to be used in conjunction with the main three-phase system (or "major star"), the transformer windings being represented by thick lines. In Fig. 9 (I) there is shown a single "hexagon," connected to two cables. The "hexagon" will be repeated on each of the arms B and C of the "major star," as may be seen in detail in the parallel case of Fig. 11, which represents, extended to all three phases, the details—shown for one phase only—of Fig. 9 (I).

In the cases of Fig. 9 (II and IV) the current from the bottom corner of the "hexagon" must be carried by a separate small cable.

The vector diagram for Fig. 9 (I) is given in detail in Fig. 10. The corners $a_1$, $a_2$, $a_3$ of the hexagons are in similar relation to the three main phases of the "major" system and may be directly supplied from the same, as may also the corners $b_1$, $b_2$, $b_3$ be similarly supplied.

It will be understood that, just as in the case of Fig. 7, power is transmitted both by the two six-phase systems and by the single-phase (or equivalent) system, and reconverted at the receiving end in the form of a joint three-phase supply on to the low-tension bus-bars, so in the case of Figs. 9 and 11 the three six-phase systems each transmit power in conjunction with the "major star" system, the latter working at from 100 000 to 150 000 volts, according to whether it is decided to risk a maximum potential gradient of 60 000 V/cm (as is, the author understands, at present under contemplation with three-phase cables) or of only 40 000 V/cm.

With regard to the actual capacitances of the various cores of the cable shown in Fig. 6, the author has worked out the various individual capacities between core and core.

The actual capacity currents required for each 15-mile section of the line are shown diagrammatically in Fig. 14. The calculations by which these figures are arrived at are shown in Appendix D.

The author has developed a simple arrangement which he thinks would be very valuable on long lines in the direction of reducing the drop due to this capacity current, and this will now be described.

## The Transmission of Charging Current through the Central Core.

Referring to Fig. 12, in the top part of the diagram is shown the way in which the aggregation of all the capacity current components of the lines involves a very heavy capacity current being sent along the outer cores from the generating station. This has rather deleterious effects on the voltage regulation of the sections of the step-up transformers and of the line.

In the lower part of Fig. 12 is shown how, by the establishment of one or two substations of comparatively small capacity along a long line (from which power would be supplied for commercial purposes for traction or lighting), it is quite practicable to "feed in" at the substations the capacity currents for the different insulation "rings" of the cable, and to transmit this current at the full 100 000 volts, re-transforming it to the local voltages required. The small hexagons shown are of course in connection with only one phase of the principal three-phase transmission (see also Fig. 11 where A, B, C represent the principal transmission).

It is arranged that at, for instance, substation No. 1 the 100 000-volt three-phase supply from the innermost cores of the six three-phase cables is taken through the three-phase primary shown, and on each phase there is generated in the secondary winding a 30 000-volt current which is fed directly, as shown, on to the correct chord of the hexagon of voltages. A feature of the author's arrangement is the following:—

A rather greater amount of reactance than the normal is introduced in each primary or secondary winding, with the result that the transformer tends to over-regulate to capacity currents and to under-regulate to load or lagging currents, again with the result that the transformer does not tend to pick up any of the load current, but does attempt to pick up a certain amount of the capacity current. This causes it to feed capacity current into the intermediate and outer cores of the cables in each direction from the substation, at the expense of an additional current in the central core. As, however, the central core is working at 100 000 volts, it is obvious that the capacity current —being only a quadrature current with reference to the load current—can be easily allowed for by a comparatively small amount of copper in the core.

By the arrangement proposed, therefore, we have greatly reduced the amount of capacity current to be passed out from the central station through the intermediate and external cores, because we can feed into the line at as many points as may be found desirable (the maximum length to be fed varies inversely as the number of feed points), and therefore the central station has now to supply only the capacity current for the said cores for the first quarter-section of line (if there is a mid-way substation).

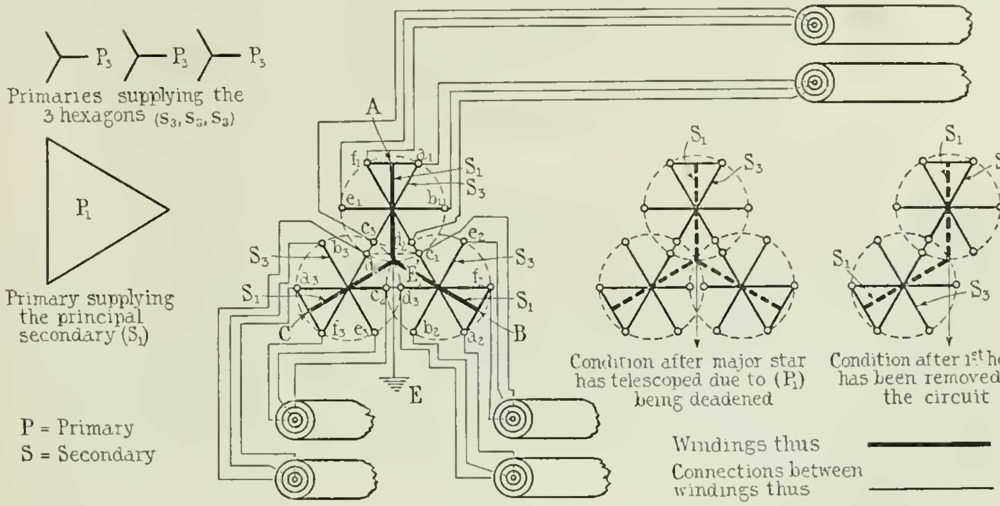

P₃
P₃
P₃
Primaries supplying the 3 hexagons (S₃, S₃, S₃)
P₁
Primary supplying the principal secondary (S₁)
P = Primary
S = Secondary
A
f₁
a₁
S₁
S₃
e₁
b₁
c₃
b₃
d₂
c₁
e₂
S₃
S₃
a₃
d₁
E
f₂
S₁
S₁
c₂
d₃
C
f₃
e₃
b₂
a₂
B
E
S₁
S₃
Condition after major star has telescoped due to (P₁) being deadened
S₁
S₃
S₁
S₃
Condition after 1st hexagon has been removed from the circuit
Windings thus
Connections between windings thus

FIG. 11.—Connections at the step-up end.

SEQUENCE OF OPERATIONS ON REDUCED LOAD.

(1) Oil switch of transformer $P_1$ is tripped (and, if faulty, the hexagon of the faulty circuit is disconnected).
(2) Earth switch is kept from neutral point Q of hexagons to earth.
(3) Hexagon No. 1 is removed.
(4) Hexagon No. 2 is removed.
(5) Hexagon No. 3 is left in.

### ADAPTING INITIAL EXPENDITURE TO INITIAL CAPACITY.

Reference may here be made to another feature of the author's system. Considering Fig. 7, it will be understood that the transmission system represented by the upper six-phase hexagon could be started, in the first instance, by itself, its bottom point being directly earthed, and thus the initial capital expenditure would be reduced. Under these circumstances the system would operate at 60 000 volts. Later, when the load developed, the second or lower six-phase system shown in Fig. 7 could be added, in such a sense that its instantaneous diametral E.M.F. would run upwards (on the diagram) at the same time as that of the upper hexagon. Its highest point, however, as well as that of the lowest point of the upper hexagon, being at earth potential, it would now be practicable to add the single-phase transformer, the secondary of which is shown by the thick, black vertical line in Fig. 8, and by this means to transmit over the same lines a single-phase superposed current at 123 000 volts, which could be similarly transformed at the distant end and would considerably increase the carrying capacity of the two six-phase systems. Lastly, when the load of the system warranted it the balance of the three-phase network, shown in Figs. 9 (I), 10 and 11 could be added and the vector relations of the E.M.F.'s could easily be altered so as to conform with Fig. 10, the 123 000-volt single-phase supply being now replaced by a 100 000-volt three-phase supply.

### V. CERTAIN FEATURES OF THE AUTHOR'S SYSTEM.

In Section (3) the advantages of a six-phase system were pointed out from the point of view of the distribution of the potentials between the various cores of the triple-concentric cables, but another point of view that must not be lost sight of is as follows :—

The employment of a six-phase system, carried from each limb of the principal three-phase transformer system, fulfils another function of great value in that it not only provides a system of subdivided cores in which all the cores must be heavy (and hence incapable of fusing under heavy capacity currents), but, in addition, it utilizes all those cores equally for the passage of heavy load currents without seriously diminished voltage on each circuit; whereas, if the same result had been attempted by the mere tapping of a single-phase transformer, as in Fig. 5, the operating voltage on one of the circuits would have been seriously lowered, and that on the other reduced to such a degree as to be virtually altogether ineffective for power transmission. This provides a sufficient excuse for returning to the employment of "intersheaths."

Greatly increased reliability in operation, whereby a duplicate cable line—such as is proposed in Appendix B, in connection with the scheme embodying plain single-core cables—is rendered unnecessary, is provided by the arrangements about to be described in the present section.

Fig. 11 gives an analysis of the arrangements, showing more particularly the way in which the line is sectionalized, whether on account of a breakdown or with the object of preserving "regulation" and reducing the (total) charging current when the load is reduced.

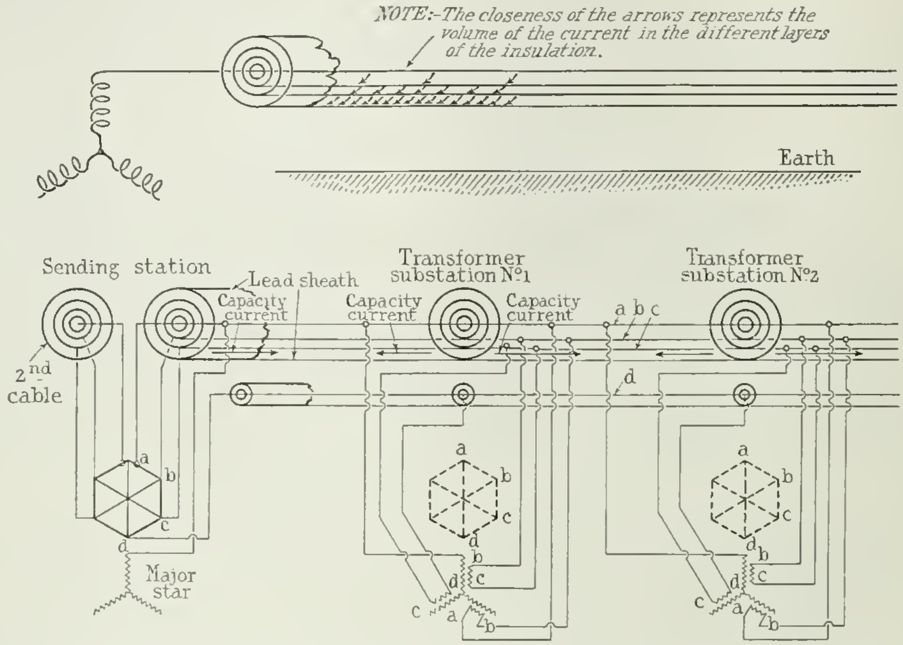

NOTE:-The closeness of the arrows represents the volume of the current in the different layers of the insulation.
Earth
Sending station
Lead sheath
Capacity current
Capacity current
Capacity current
Transformer substation No1
Transformer substation No2
a b c
d
2nd cable
a
b
c
d
Major star
a
b
c
d
b
c
d
c
a
b
a
b
c
d
b
c
d
c
a
b

FIG. 12.—Arrangement for relieving the cores of capacity current in the case of a very long line. (*Note.*—Currents in "b" are, for clearness, omitted.)

An advantage of the proposed scheme is that if, for example, the two cables attached to phase A (see Fig. 11) were both to fail, when, in the ordinary way of operating three-phase systems, no three-phase power could any longer be transmitted, the two remaining six-phase systems may, in the author's system, be arranged to continue to work as though nothing had happened. If, moreover, only one cable had failed, and not two, then three-phase power could still have been transmitted over the "major star" system ABC (using the remaining sound cable for the third leg) in addition to six-phase power over two out of the three six-phase systems. (It will be shown later in the paper that the chance of even one cable completely breaking down sufficiently to be incapacitated is very much more remote than with an ordinary single-core cable.)

Thus—and this would be still more feasible under the conditions shown in Fig. 9 (IV)—with a little overloading of the transformers the whole power supply could be maintained; particularly if the central core of each cable were made of double section, which would not appreciably raise the cost of the whole cable at the voltage considered. In connection with the reliability in working thus offered, Mr. Philip Torchio of New York has stated that "the assuring of reliable operation is vastly more important than getting the maximum rating out of a certain mass of metals."

The sectionalizing of the system incidentally provides also a means: (1) of insuring regulation without the use of rotary condensers, and (2) of greatly reducing the charging current of the line at light loads. For example, if, on a reducing load, the various sections of transformers be de-electrified in the order indicated in Fig. 11, then each section of the line and transformers remaining in service is kept fully loaded, and thus capacity current-rises are avoided.

The total line-charging current (a very important matter) and also the total hysteresis loss are similarly reduced, by the fact that progressively less and less cable is left in circuit.

The design of the cable itself is particularly suited to avoid breakdown (due to outside influences), as will be appreciated from Fig. 6, which shows a cross-section of the cable.

The function of the internal lead sheath will be understood from the following considerations:—

Cables, as laid nowadays, are fairly immune from the blow of a pick; but the lead sheath may crack, or crystallize, or possibly be attacked by acids or by electrolysis.

The first intimation of a fault is given by the failure of the outermost insulation. If this is made to trip immediately, in the first place, the oil switch governing whichever of the transformers $P_3$ (see Fig. 11) feeds the faulty six-phase circuit, and simultaneously the "major" transformer $P_1$ feeding that section (and assuming that the action has been sufficiently rapid to prevent the copper of the outer conductor being burnt through), we have the penultimate lead sheath still unpierced and the cable still capable of working —under slightly increased stress—for days if necessary, until a spare piece of cable can be connected in the secondary side of the step-up transformer at a time of light load. If there were no inner lead sheath below the core, moisture would reach the insulation, and it might only be a question of hours before it again broke down. The three independent six-phase systems permit of repair work being done without any material interruption to the supply, at times of light loads.

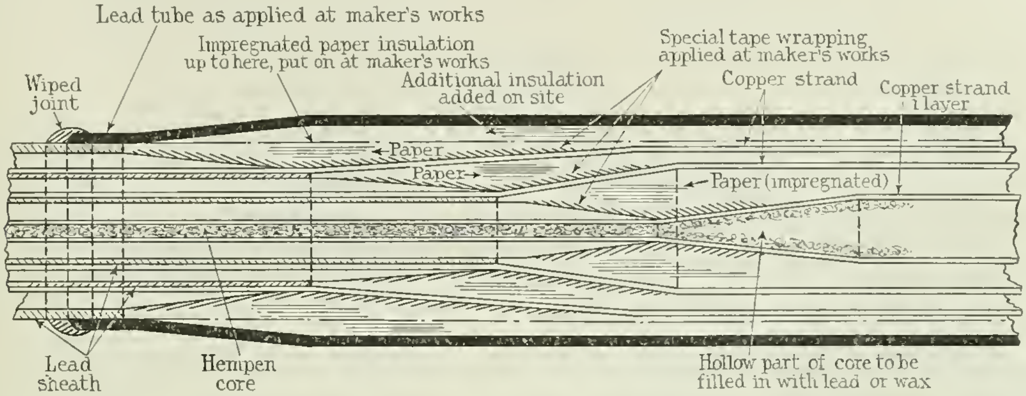

Lead tube as applied at maker's works
Impregnated paper insulation up to here, put on at maker's works
Additional insulation added on site
Special tape wrapping applied at maker's works
Copper strand
Copper strand 1 layer
Wiped joint
Paper
Paper
Paper (impregnated)
Lead sheath
Hempen core
Hollow part of core to be filled in with lead or wax

FIG. 13.—Method of finishing-off the end of the cable so as to reduce the potential gradients at the approach to a joint; performed at makers' works.

The cable shown in Fig. 6 has been designed to work at about 30 000 volts between the innermost conductor and the intermediate conductor, at an equal pressure between the intermediate conductor and the outermost conductor, and with about 17 800 volts between the outermost conductor and the lead sheath. Under these conditions the maximum potential gradient on the innermost and intermediate conductors will be approximately 39 000 and 29 000 V/cm respectively, while that on the outermost conductor will be about 20 000 V/cm.

At the joints the potential gradient could be kept down by swelling the conductors gradually, in the manner indicated in Fig. 13. Those parts where the potential gradient was highest would be entirely insulated at the makers' works as shown, leaving a reduced stress to be borne by those parts insulated on site.

### HYSTERESIS LOSS.

The loss due to hysteresis on the 100 000-volt three-phase/six-phase system is only about 1·9 per cent on a 30-mile line, or about 0·9 per cent more than with a 30 000-volt transmission of equal power (50 000 kW), but on a 40 per cent load factor this would be halved on the former system.

### REGULATION.

The regulation voltage-drop in the 30 000-volt line discussed in Appendix A for a 30-mile line is 5·9 per cent; while the total amount of copper is 2 040 tons, representing an outlay of, say, £180 000. The regulation "drop" in the 100 000-volt 30-mile line discussed in Appendix B (plain single-core cables) is 4·5 per cent, while the total amount of copper is 460 tons, representing an outlay of, say, £41 400.

On the six-phase/three-phase system the regulation "drop" is roughly 5 per cent, and the amount of copper about 700 tons, representing an outlay of, say, £63 000. These quantities would be divided by three for a 10-mile line.

The author thinks it will be conceded that where a trunk line interlinking two cities is run along the lines of railway joining these two cities, and where there is any possibility of supplying current from such a trunk line for the working of the railway system, it is highly desirable that the regulation of the line should be so good that the throwing on and off of the railway loads will not seriously affect the regulation at the substation end; also that, allowing for the additional loss in regulation after the public supply of current leaves the substation, in distribution, it is inadvisable that the regulation of the trunk line, including its step-up and step-down transformers, should be more than 12½ per cent. By fixing the declared voltage at that obtained on half load the variation of voltage is of course reduced from 12½ per cent to 6¼ per cent.

The author thinks it will also be conceded that induction regulators, to cover a large range in the voltage and operate automatically, are very costly and undesirable, particularly if they can be dispensed with.

It will be noted from Appendix A that, in the case of the 30 000-volt line considered, the resistance-drop is of the order of 3·3 per cent, the reactance-drop of the order of 1·6 per cent, and the capacity-rise of the order of 1 per cent; i.e. a total "regulation" of 5·9 per cent on the line alone. If to this we add, say, 4½ per cent on the step-up transformers (due largely to capacity current), and 3½ per cent on the step-down transformers, we have a total of 13·9 per cent, or, say, 14 per cent, which is rather high for satisfactory regulation in view of what has been stated above.

It will possibly be objected that the author has done an injustice to the 30 000-volt scheme in adopting for this a current density of only 500 amperes per square inch, and that half the number of cables could be employed, working at a current density of 1 000 amperes per square inch. If, however, this were done, and regardless of the extra energy loss in the cables (which will be dealt with elsewhere), the "regulation" of the cables and transformers would be increased from 13·9 per cent to 19·8 per cent, and the author submits that the latter regulation is entirely impracticable without a very great outlay in induction regulators and considerable expense in the maintenance of the same.

On the other hand, by adopting a pressure of 100 000 volts and using single-core cables, the line drop (exclusive of transformers) is reduced to 4½ per cent, as given in Appendix B, and thus the total regulation becomes only 12½ per cent, as against 19·8 per cent on the 30 000-volt scheme with 5 cables in parallel.

As already explained, by suitably fixing the declared voltage this variation may be halved, but even 6¼ per cent is distinctly high, and it may be necessary to eliminate the regulation of the step-up transformers by operating at the generating station with a constant voltage on the high-tension secondaries, instead of attempting to keep the low-tension busbars at a constant pressure. If there are any large loads in the vicinity of the station which are supplied from the low-tension busbars, the regulation of this section of the system will of course be impaired, and the employment of regulators on the primary or secondary sides of the transformers may be necessary, or, alternatively, a step-down transformer may be used for the local load.

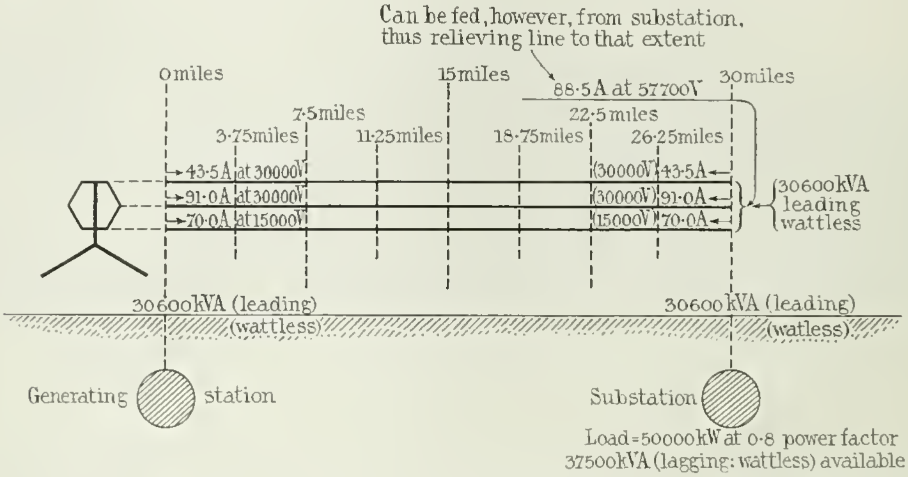

Can be fed, however, from substation, thus relieving line to that extent
0 miles
15 miles
30 miles
88·5 A at 57700V
7·5 miles
22·5 miles
3·75 miles
11·25 miles
18·75 miles
26·25 miles
43·5 A at 30000V
91·0 A at 30000V
70·0 A at 15000V
(30000V) 43·5 A
(30000V) 91·0 A
(15000V) 70·0 A
30600 kVA leading wattless
30600 kVA (leading) (wattless)
30600 kVA (leading) (watless)
Generating station
Substation
Load = 50000 kW at 0·8 power factor
37500 kVA (lagging: wattless) available

Fig. 14.—Distribution of capacity currents on 100 000-volt transmission. No demand on substation for lagging wattless current.

### Charging Current.

The charging current for 30 miles on the author's system represents 61 200 kVA leading wattless current, but at light loads this would be reduced to roughly 20 000 kVA, which is less than would obtain with a 30 000-volt system transmitting equal power (the figure for which is approximately 33 500 kVA), and entirely neglects the possible savings due to the better distribution of heat, and consequently greatly lowered power factor, which was discussed earlier in the paper.

The calculations by which the figure of 61 200 kVA is arrived at will be found in Appendix D, in connection with the capacities on the author's system, and the results there obtained are represented diagrammatically in Fig. 14.

### Charging Current fed from Reactance of Motor Load.

With suitable precautions to avoid "current resonance," the author believes that the necessary charging currents may be fed into the line at convenient points in such a way as to avoid passing any charging current along the central cores, thus opening up the possibility of removing the disability under which a.c. transmission now labours as compared with d.c. transmission. This method has not, however, been considered in the calculations given in Appendix D.

Fig. 15 illustrates the resultant distribution of capacity currents under these conditions.

On such a line, loads having a power factor of only 0·7 would be invited, and a.c. railway electrification with single-phase motors at 25 periods might, in some cases, be employed if otherwise found desirable.

## VI. Reasons for the Selection of 10 Cables on a 30 000-volt Scheme.

It will be well here to state the reasons which determined the author in selecting what is apparently a very large number of cables in parallel to deal with the load under consideration.

It has already been explained that, on questions of regulation alone, it appeared to be a necessity that 10 cables should be employed, on the assumption that it was undesirable to make the cables of greater sectional area than 0·25 square inch per core.

There is, however, the alternative point of view to be considered, viz. as to whether the additional waste of energy involved by using only 5 cables would not cost more, when capitalized, than the difference in price between 5 cables and 10 cables. This point the author has investigated carefully, with the following results: On an output of 7 500 kW (the figure taken by Mr. W. M. Selvey*), with 8 000 hours per annum (91·5 per cent load factor), and with coal at 0·15d. per unit generated, the annual value of 600 000 units wasted (corresponding to 1 per cent of the total number of units generated) would represent £375.

For the purpose of showing the value of each additional 1 per cent of efficiency gained in the generating plant, Mr. Selvey took an 8-years' basis and capitalized the above £375 per annum at £3 000. From this he deduced that it would pay, on a plant of the above magnitude, to spend an extra £3 000 on generating plant (which had a life of only 8 years) in order to gain 1 per cent in efficiency, i.e. in order to save 1 per cent of the power. In other words, the sum of £375 saved every year would enable one to continue to spend an additional £3 000 once very 8th year on a more efficient generating plant, when one renewed the latter.

If, however, we are dealing with a transmission cable which has a life of, at the very least, 16 years, it will obviously pay to invest an additional £6 000 (i.e. double) for an equal 1 per cent saving in the $I^2R$ losses in the line.

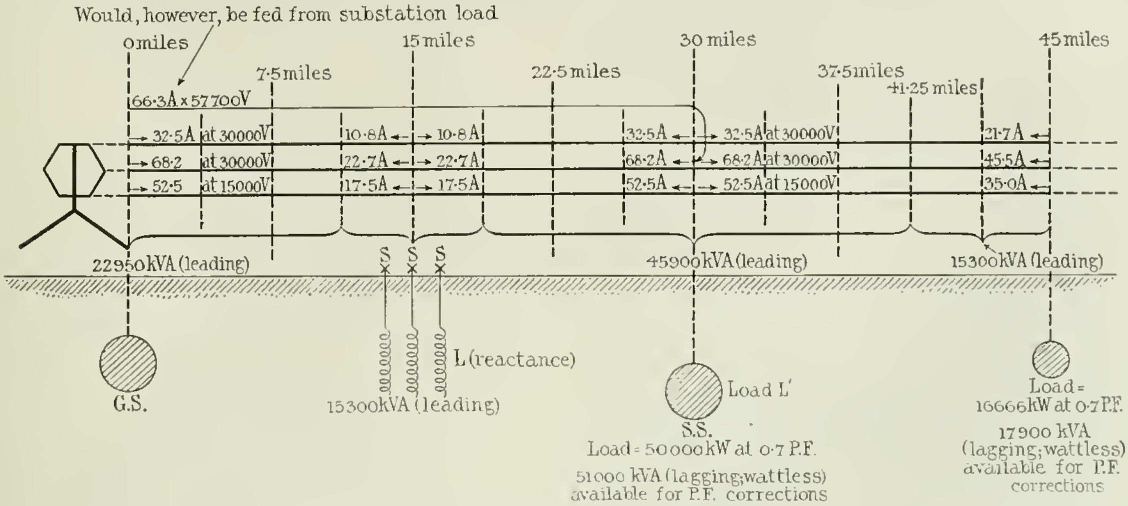


FIG. 15.—Distribution of capacity currents on 100 000-volt transmission. Lagging wattless current supplied from substation load.

Converting the above figures to our present case, we have:—

$$£6\,000 \times \frac{0\cdot 5\text{d.}}{0\cdot 15\text{d.}} \times \frac{50\,000 \text{ kW}}{7\,000 \text{ kW}} \times \frac{40\ \% \text{ load factor}}{91\cdot 5\ \% \text{ load factor}} = £58\,300$$

In other words, it will pay to invest £58 300 in extra copper in the transmission line in order to save 1 per cent of the total power generated.

The 0·5d. per unit is for the supply to the substation, but as the line loss is a peak load loss, and varies with the square of the load, and has in consequence a poorer load factor than the load itself, these waste units will certainly be more expensive than units sold to the substation for power, and they should therefore be charged at a higher rate.

The following is another way of regarding the matter: An extra 1 000 kW demanded at the generating station means the loss of the sale of that power (less losses) to a consumer, and the loss of the revenue that would thereby accrue, and therefore covers all charges up to the consumer's premises; and if in addition to this we make an allowance for the poor load factor of the $I^2R$ losses in the transmission line, this proportionately further aggravates the charge.*

It seems advisable, in view of the above, to correct the charge per unit for a "loss" load factor of, say, 30 per cent ($I^2R$ losses), and hence to multiply the above figure of £58 300 by 40/30, which gives £77 800 as the capitalized value of a 1 per cent loss in the line.

Referring now to Appendix A, we see that the losses consist of

3·3 per cent plus 1·58 per cent plus 3·55 per cent (wattless current × resistance)
= 8·4 per cent total as a sufficiently near approximation.

---

* W. M. SELVEY: "Power Plant Testing," *Journal I.E.E.*, 1915, vol. 53, p. 109.

* In this connection, see the remarks by Messrs. J. R. Beard, J. A. Morton, and H. M. Sayers in the discussion on Mr. W. B. Woodhouse's paper (*Journal I.E.E.*, 1921, vol. 59, p. 85).

Hence, 8·4 times £77 800 = £653 000; and therefore, in order to make it pay to put 5 cables in parallel instead of 10, the difference in capital cost should be of the order of £653 000, to which would have to be added, say, £50 000 (to £100 000) on account of induction regulators, making a total of, say, £703 000.

The author has therefore assumed that it will be agreed that, quite apart from the question of regulation, it is the best policy to put down the double section of copper, even though this entails working at a comparatively low current density.

## VII. CONCLUSIONS.

It is hoped that the following points have either been established or will be clear from the matter given in the paper :—

(1) By the introduction of intersheaths between which a *constant* difference of potential is maintained (see Table 2, page 234) a gain of 47 per cent is effected in the voltage absorbed, for a given thickness of insulation.

(2) By the introduction of intersheaths having a steadily *increasing* difference of potential between them, working from the central core outwards (see Table 3, page 234) a further gain of 50 per cent—i.e. a total gain of 120 per cent—is effected in the voltage absorbed, without appreciably more energy loss in the dielectric than in the case of Table 2.

(3) The enormous effect of temperature upon the resistivity of the dielectric warrants the employment of any conceivable methods—such as those indicated in the paper—which will relieve the temperature on the innermost layers of the dielectric.

(4) The separation of the principal phases in the system proposed, or in any single-core system, carries with it a much greater freedom from complete short-circuits.

(5) Double reliability is offered by having two cables per (principal) phase, this being approximately equivalent to a spare cable and, in the case of a single-core 100 000-volt system, to two spare cables.

(6) The virtual elimination of all faults, except those to earth, is effected, and interruptions caused by such faults are reduced to such a degree that the working of the system is not seriously affected.

(7) Considerable improvement in step-up and step-down transformer regulation is provided, as compared with that in three-core cable systems operating at 30 000 volts, or single-core systems operating at 100 000 volts.

(8) The initial capital outlay is limited to the natural growth of the load.

(9) As compared with a 30 000-volt three-core cable, there is no waste space in the centre of the cable.

(10) Assuming that the line can be made self-exciting, the difficulty in connection with feeding the capacity currents to the line disappears, and very much longer transmissions can be attempted than would otherwise be practicable; or are considered in the paper.

The author wishes to acknowledge, with many thanks, the assistance which he has received in compiling the paper and the following Appendixes, from the following firms :—Messrs. Callender's Cable and Construction Co., Ltd., Messrs. Henley's Telegraph Works Co., Ltd., Messrs. British Insulated and Helsby Cables, Ltd., Messrs. W. T. Glover and Co., Ltd., and Messrs. Pirelli General Cable Works, Ltd. (cable companies); Messrs. Reyrolle and Co., Ltd., Messrs. British Thomson-Houston Co., Ltd., Messrs. Metropolitan-Vickers Electrical Co., Ltd., and Messrs. General Electric Co., Ltd. (switchgear companies); and Messrs. Metropolitan-Vickers Electrical Co., Ltd., Messrs. Brush Electrical Engineering Co., and Messrs. Johnson and Phillips, Ltd. (transformer companies).

## APPENDIX A.

### ORDINARY THREE-PHASE WORKING.

Power to be delivered = 50 000 kW at 0·8 power factor.

Voltage at receiving end = 30 000 V.

Length of line = 30 miles.

Cable used: ordinary three-core cable (as in Fig. 16).

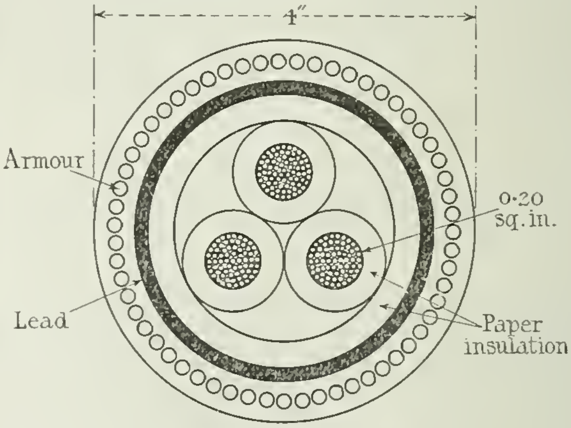


FIG. 16.—Cable for 30 000-volt transmission.

Resultant current per phase = 1 200 amperes. (This current will be passed through ten 0·25 square inch cables in parallel, excluding spares.)

"Work" component of the above current = 960 amperes ($I_L$).

Lagging component = 728 amperes ($I_W$).

Current density = 120/0·25 = 500 amperes per square inch (neglecting capacity current).

Capacity current $= b \times E = 0\cdot00372 \times 17\,320 = 64\cdot5$ amperes per cable.

Total capacity current (10 cables) = 645 amperes.

The figure 0·25 sq. in. for the cross-section is somewhat unduly liberal, but is retained in order to keep the copper voltage-drop within reasonable limits.

Take, therefore, in comparing copper weights, the following :—

Total cross-section of copper = 0·25 sq. in. × 3 cores (per cable) × 10 cables = 7·5 sq. in.

The amount of copper involved = 2 040 tons per 30 miles.

Below are the calculations giving the various components of the E.M.F. with their phase relations :—

$I = 960A - j728A$ (0·8 power factor).

$r = 0\cdot2$ ohm × 30 miles = 6·0 ohms (hot).

$x = (0\cdot4 \times 10^{-3}) \times 2\pi f \times 30 = 3\cdot76$ ohms.

$b = 2\pi fC = 6\cdot28 \times 50 \times (0\cdot4 \times 10^{-6}) \times 30$ miles.

$= 0\cdot00372$ mho.

$$\left.\begin{array}{l} Z=r+jx=6\cdot0+j3\cdot76 \\ Y=g+jb=0+j0\cdot00372 \end{array}\right\} \begin{array}{l} \therefore ZY=j0\cdot0223-0\cdot014. \\ \therefore \tfrac{1}{2}ZY=-0\cdot007+j0\cdot0111. \end{array}$$

$1 + \frac{1}{2}ZY = +\,0\cdot993 + j0\cdot0111.$

$$E_G = E_R(1 + \tfrac{1}{2}ZY) + (r + jx)(I_L/10 + jI_W/10)$$

$$= 17\,320\,(\underset{(1-\frac{1}{2}bx)}{0\cdot993} + \underset{(j.\frac{1}{2}br)}{j0\cdot0111})$$

$$+ (\underset{(r)}{6\cdot0} + \underset{(jx)}{j3\cdot76})\,(\overset{I_L}{960A/10} - \overset{jI_W}{j728A/10})$$

$$= \underset{\substack{E_R-E.\frac{1}{2}bx\\(17\,320-170)\\ 1\%}}{17\,150} + \underset{1\cdot1\%}{\overset{jE.\frac{1}{2}br}{j193}} + \underset{3\cdot3\%}{\overset{rI_L}{576}} - \underset{2\cdot45\%}{\overset{jrI_W}{j425}} + \underset{2\cdot1\%}{\overset{jxI_L}{j360}} + \underset{1\cdot58\%}{\overset{xI_W}{274}}.$$

Total regulation " drop " $= rI_L + xI_W + \frac{1}{2}bEx.$

$= 3\cdot3\,\% + 1\cdot58\,\%$
$+ 1\cdot0\,\% =$ (say) $5\cdot9\,\%$.

## APPENDIX B.

### Plain Single-core Scheme (see Fig. 1) with 100 000 Volts between Phases.

Power to be delivered = 50 000 kW at 0·8 power factor.

Length of line = 30 miles.

Cable employed : as shown in Fig. 1, 6 single-core 0·185 sq. in. cables (100 per cent spares included).

Voltage at receiving end = 57 700 volts (to neutral).

Resultant receiver current, neglecting capacity current = 360 amperes per phase.

" Work " component of the above current = 288 amperes ($I_L$).

" Lagging " component = 216 amperes ($I_W$).

Current density = 1 000 amperes per square inch (excluding capacity current), = 1 400 amperes per square inch (including capacity current).

Capacity current = $b \times E = 0\cdot0033 \times 57\,700$, = 190 amperes per cable.

Total capacity current (2 cables) = 380 amperes.

Below are given the components of the voltage lost in the line, and their phase values.

The preliminary calculations for the various " constants " of the line are as follows :—

$I = I_L - jI_W.$

$= 288A - j216A$ (0·8 power factor).

$r = 0\cdot27$ ohm × 30 miles = 8·1 ohms (hot).

$L = 0\cdot4605 \log_{10} b/a + 0\cdot05 + L'$ (negligible).

$= 0\cdot70 \times 10^{-3}$ henry.

$x = (0\cdot70 \times 10^{-3}) \times 2\pi f \times 30 = 6\cdot6$ ohms.

$$C = \frac{0\cdot0388 \times 3\cdot2}{\log_\epsilon b/a} = 0\cdot35\,\mu\text{F per mile.}$$

$b = 2\pi fC = 6\cdot28 \times 50 \times (0\cdot35 \times 10^{-6}) \times 30$ miles

$= 0\cdot00330$ mho.

$$\left.\begin{array}{l} Z=r+jx=8\cdot1+j6\cdot6 \\ Y=g+jb=0+j0\cdot0033 \end{array}\right\} \begin{array}{l} \therefore \tfrac{1}{2}ZY=-0\cdot0109+j0\cdot0133 \\ \qquad =j0\cdot0267-0\cdot0218. \end{array}$$

$1 + \frac{1}{2}ZY = 0\cdot9891 + j0\cdot0133.$

$$E_G = E_R(1 + \tfrac{1}{2}ZY) + (r + jx)\,(\tfrac{1}{2}I_L + jI_W).$$

$$= 50\,770\,(0\cdot9891 + j0\cdot0133)$$

$$+ (8\cdot1 + j6\cdot6)\,(\overset{I_L}{288A/2} - \overset{jI_W}{j216A/2}).$$

$$= 57\,700 - \underset{1\cdot25\%}{\overset{(\frac{1}{2}bEx)}{700}} + \underset{1\cdot33\%}{\overset{j(\frac{1}{2}bEr)}{j768}} + \underset{2\cdot0\%}{\overset{rI_L}{1\,165}} - \underset{1\cdot5\%}{\overset{jrI_W}{j882}} + \underset{1\cdot65\%}{\overset{jxI_L}{j950}} + \underset{1\cdot25\%}{\overset{xI_W}{710}}$$

Total regulation " drop " $= rI_L + xI_W + \frac{1}{2}bEx.$

$= 2\cdot0\,\% + 1\cdot25\,\%$
$+ 1\cdot25\,\% = 4\cdot5\,\%$.

The amount of copper involved, allowing for 3 sets of cables = 460 tons per 30 miles.

*Note.*—The leakage conductance ($g$) of the dielectric has been neglected in the above calculations. In a more rigorous calculation account would have to be taken of it (see additional Note in Appendix D on this subject).

## APPENDIX C.

### Further Remarks on the Question of Potential Gradients.

The following notes give the result of a continued investigation on the lines indicated in Section III of the paper.

In Table 1 are given in tabulated form the values of

(1) The capacity of the 1st, 2nd, 3rd, 4th, . . . 10th, etc., layers of insulation, working outwards.
(2) The corresponding capacity current passing radially through these layers.
(3) The watts lost in each layer.
(4) The voltage differences across each layer.
(5) The volume of each layer, in cubic centimetres.
(6) The watts per cubic centimetre.
(7) The maximum potential gradient on each successive section.

It will be observed that the total voltage absorbed down to the end of the tenth layer is 41 250 volts. The above figures merely correspond to development further outwards on the cable of the figures given in Fig. 3, and assume the curve of potential gradient to follow that given in Fig. 3.

In Table 2 corresponding figures are given, but this time on the assumption that the voltages between successive equipotential surfaces are constant at 8 750 volts, instead of diminishing according to the figures given, as in Table 1. In this case it will be observed that after reaching the fifth ring of insulation, cor-

TABLE 1.

*Decreasing Voltage Differences between Successive Layers.*

| $C \times 10^{-6}$ per foot | Capacity current ($= i_d \times 10^{-3}$ $= 2\pi fCE$) | Watts lost ($= W_d$ per foot) | Voltage absorbed, $E$ | Value of $\log_\epsilon \frac{b}{a}$ | Relative contents of each layer | Watts per cm³ | Max. potential gradient, $G$ |
|---|---|---|---|---|---|---|---|
| | | | | | cm³ | | |
| 0·000124 | 0·341 | 0·0450 | 8 750 | 0·432 | 54 | 0·000834* | 30 000 |
| 0·000131 | 0·320 | 0·0370 | 7 720 | 0·405 | 117 | 0·000316 | 19 050 |
| 0·000185 | 0·321 | 0·0270 | 5 700 | 0·288 | 165 | 0·000163 | 13 000 |
| 0·000238 | 0·322 | 0·0200 | 4 030 | 0·223 | 213 | 0·000094 | 9 510 |
| 0·000302 | | 0·0170 | 3 550 | 0·184 | 261 | 0·000065 | 7 800 |
| | | | 29 750 | | | | |
| 0·000351 | | 0·0140 | 2 890 | 0·152 | 306 | 0·000046 | 6 350 |
| 0·000399 | $0·32 \times 10^{-3}$ | 0·0120 | 2 500 | 0·131 | 354 | 0·000034 | — |
| 0·000461 | (constant) | 0·0110 | 2 230 | 0·117 | 402 | 0·000027 | — |
| 0·000511 | | 0·0097 | 2 020 | 0·106 | 450 | 0·000021 | — |
| 0·000560 | | 0·0085 | 1 840 | 0·097 | 489 | 0·000017 | — |
| | | 0·2012 | 41 250 | | 2 820 | | |

TABLE 2.

*Constant Voltage Differences between Successive Layers.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0·000124 | $0·341 \times 10^{-3}$ | 0·0450 | 8 750 | 0·432 | 54 | 0·000834* | 30 000 |
| 0·000131 | 0·362 | 0·0472 | 8 750 | 0·405 | 117 | 0·00040 | 21 600 |
| 0·000185 | 0·491 | 0·0635 | 8 750 | 0·288 | 165 | 0·00038 | 20 000 |
| 0·000238 | 0·694 | 0·0940 | 8 750 | 0·223 | 213 | 0·00044 | 20 500 |
| 0·000302 | 0·790 | 0·1030 | 8 750 | 0·184 | 261 | 0·000396 | 19 250 |
| 0·000351 | | | | | | | |
| 0·000399 | | 0·3527 | 43 750 | | 810 | | |
| 0·000461 | | | | | | | |
| 0·000511 | | | | | | | |
| 0·000560 | | | | | | | |

75 per cent more (total) loss than with "tapering" E.M.F.

TABLE 3.

*Increasing Voltage Differences between Successive Layers.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | $1/(\log_\epsilon b/a)$ | | | |
| 0·000124 | 0·227 | 0·020 | 5 820 | 2·31 | 54 | 0·000370* | 20 000 |
| 0·000131 | 0·340 | 0·045 | 8 920 | 2·47 | 117 | 0·000385 | 22 000 |
| 0·000185 | 0·615 | 0·098 | 10 600 | 3·47 | 165 | 0·000594 | 24 200 |
| 0·000238 | 0·843 | 0·142 | 11 300 | 4·48 | 213 | 0·000668 | 26 600 |
| 0·000302 | 1·270 (0·635) | 0·259 (0·0635) | 13 320 (6 660) | 5·44 | 261 | 0·000486 | 29 300 |
| 0·000351 | | | | | | | |
| 0·000399 | | 0·559 (0·368) | 49 960 (43 300) | 6·58 | 810 | | |
| 0·000461 | | | | | | | |
| 0·000511 | | | | | | | |
| 0·000560 | | | | | | | |

4 per cent more (total) loss than with constant voltage per section.

---

* The first layer, not being a full half centimetre thick, is not properly representative of the others.

responding to a radius of 3 cm, 43 750 volts has been absorbed in the insulation. It will also be noticed that the watts lost in the insulation up to this point due to the condenser current alone are now 0·3527 as against 0·2102 in Table 1, i.e. an increase of 75 per cent. The watts lost per cubic centimetre on the innermost layer are, however, identical with those in Table 1 and this is the criterion by which we have to abide (from the point of view of heating).

Therefore, in putting relatively more stress upon the succeeding layers as we work outwards, as compared with those in Table 1, we have reduced the effective radius of the insulation from 5 cm to 3 cm, i.e. the size of the cable necessary to absorb 43 750 volts would be reduced in that proportion. The comparison would be much more marked if we had carried the readings in Table 1 further, as will be evident from a consideration of these readings.

In Table 3 particulars similar to those given in Tables 1 and 2 are worked out, but this time on the basis of actually increasing the voltage differences between the successive layers, instead of keeping them constant as in Table 2 or reducing them as in Table 1. It will be seen that the potential gradient in the ring of insulation next to the core is now reduced to as low as 20 000 V/cm as compared with 30 000 V/cm in Tables 1 and 2. By adding up the voltages absorbed it will be seen from Table 3 that 49 960 volts have been absorbed by the time the 3 cm radius has been reached. This is more than is required and therefore the pressure upon the outermost slice of insulation might be considerably reduced, as shown, for instance, by the figures given in brackets. It will be noted that if we had not reduced the potential gradient of this outermost slice the total watts lost due to hysteresis would be rather more, namely 0·559, but that if the pressure is reduced to 6 660 volts the total watts lost will only be 0·368, a result virtually identical with that obtained in Table 2, but with the great advantage of reducing by over 50 per cent the watts per cm$^3$ next to the core.

Bearing in mind what was previously put forward, viz. that, in the ordinary working of the cable, the heat generated in the copper core due to the load current causes the slices of insulation to be progressively hotter towards the centre of the cable, it will be seen that a great advantage would be obtained by generating the greater proportion of the heat due to dielectric hysteresis in the slices of insulation that are naturally at a much lower temperature, and in which, instead of the dielectric power factor remaining constant from the central core outwards, as is assumed in Tables 1, 2 and 3, it would consequently be diminishing, with still better results than those shown in the tables.

In addition to the above it must be remembered that not only does the heat due to the loss in the copper produce temperatures in the innermost layers of insulation greatly above those in the exterior layers, but that the conductance losses due to pure leakage of current (which are not taken account of in Tables 1, 2 and 3), also produce heating under conditions precisely similar to those of dielectric hysteresis. The advantage gained in the dielectric hysteresis loss is practically doubled (and may be quadrupled) by that gained in the pure conductance loss through the dielectric.

## APPENDIX D

### Calculations of Capacities of Triple-concentric Cables.

Referring to Fig. 6, let the innermost, intermediate and outermost cores be designated $a$, $b$ and $c$, respectively, and let the lead sheathing be designated $d$.

Let the dimensions be as follows :—

| | cm |
|---|---|
| Radius of $a$ .. .. .. .. .. | 0·835 |
| Radius to interior surface of core $b$ .. .. | 2·105 |
| Radius to exterior surface of core $b$ .. .. | 2·300 |
| Radius to interior surface of lead sheathing underneath core $c$ .. .. .. .. | 3·570 |
| Radius to exterior surface of lead sheathing underneath core $c$ .. .. .. .. | 3·920 |
| Radius to exterior surface of core $c$ .. .. | 4·120 |
| Radius to interior surface of external lead sheathing .. .. .. .. .. | 5·120 |
| Radius to exterior surface of external lead sheathing .. .. .. .. .. | 5·570 |

The capacities per mile of the three insulations are obtained as follows :—

$$C_{a/b} = \frac{0\cdot0388 \times 3\cdot2}{\log_{10}(2\cdot10/0\cdot835)} = 0\cdot3095 \times 10^{-6} \text{ farad}$$

$$C_{b/c} = \frac{0\cdot0388 \times 3\cdot2}{\log_{10}(3\cdot57/2\cdot30)} = 0\cdot647 \times 10^{-6} \text{ farad}$$

$$C_{c/d} = \frac{0\cdot0388 \times 3\cdot2}{\log_{10}(5\cdot12/4\cdot12)} = 1\cdot00 \times 10^{-6} \text{ farad}$$

The total capacities for 30 miles are therefore :—

$$C_{a/b} = 0\cdot3095 \times 10^{-6} \times 30 = 9\cdot27 \times 10^{-6} \text{ farad}$$
$$C_{b/c} = 0\cdot647 \times 10^{-6} \times 30 = 19\cdot5 \times 10^{-6} \text{ farad}$$
$$C_{c/d} = 1\cdot00 \times 10^{-6} \times 30 = 30\cdot0 \times 10^{-6} \text{ farad}$$

The capacity currents through the three insulations are :—

$$I_{a/b} = b_{a/b} \times E = 2\pi \times 50 \sim \times (9\cdot27 \times 10^{-6}) \times 30\,000 \text{ V} = 87\cdot2 \text{ A}$$

$$I_{b/c} = b_{b/c} \times E = 2\pi \times 50 \sim \times (19\cdot5 \times 10^{-6}) \times 30\,000 \text{ V} = 183\cdot5 \text{ A}$$

$$I_{c/d} = b_{c/d} \times E = 2\pi \times 50 \sim \times (30 \times 10^{-6}) \times 15\,000 \text{ V} = 141\cdot5 \text{ A}$$

Now,

87·2 A × 30 000 V = 2 610 kVA; or 57 700 V × 45·2 A
183·5 A × 30 000 V = 5 500 kVA; or 57 700 V × 95·4 A
141·5 A × 15 000 V = 2 120 kVA; or 57 700 V × 36·8 A

kVA per cable = 10 230
Current per cable (central core) = 177·4 A

Taking the power factor at 1·5 per cent, the kilowatt loss due to dielectric hysteresis alone (i.e. neglecting leakage conductance loss) is :—

10 230 kVA × 0·015 × 6 (cables) = 918 kW

which is 918/50 000 = 1·84 per cent of the power transmitted.

Total kVA capacity (wattless leading current) for a 30-mile section

$$= 10\,230 \text{ kVA per cable} \times 6 \text{ (cables)}$$
$$= 61\,200 \text{ kVA (approx.)}$$

### Resistivity Loss in Dielectric.

The following first approximation to the resistivity loss (i.e. the 'leakage conductance" loss) in connection with the author's system has been worked out, on the basis of the specific average effective resistivity per cubic centimetre being taken at $100 \times 10^{10}$ ohms at 23° C. and at a potential gradient of 40 kV/cm; and the formula used is as follows:—

$$\text{Watts per cm length of cable} = \frac{E^2}{\frac{\rho_{(av.)}}{2\pi l}\int_a^b \frac{1}{r}dr} = \frac{2\pi l \,.\, E^2}{\rho_{(av.)} \log_\epsilon (b/a)}$$

where $\rho_{(av.)}$ = average effective resistivity per cubic centimetre,
= (say) $100 \times 10^{10}$ ohms per cubic centimetre; at 25° C. and at 40 kV/cm.

From the above formula we obtain:—

$$W_{a/b} \text{ (per mile)} = \frac{6\cdot28 \times (5\,280 \times 30\cdot5) \times 30\,000^2}{100 \times 10^{10} \times 2\cdot30 \times \log_{10}(2\cdot105/0\cdot835)}$$
$$= 985 \text{ watts (per cable)}$$

$$W_{b/c} \text{ (per mile)} = \frac{6\cdot28 \times (5\,280 \times 30\cdot5) \times 30\,000^2}{100 \times 10^{10} \times 2\cdot30 \times \log_{10}(3\cdot57/2\cdot30)}$$
$$= 2\,055 \text{ watts (per cable)}$$

$$W_{c/d} \text{ (per mile)} = \frac{6\cdot28 \times (5\,280 \times 30\cdot5) \times 15\,000^2}{100 \times 10^{10} \times 2\cdot30 \times \log_{10}(5\cdot12/4\cdot12)}$$
$$= 795 \text{ watts (per cable)}$$

Total watts (per cable) = 3 835
Total per 30 miles of cable = 115 050
= 115 kW per cable.

Now,

$$\frac{115 \text{ kW} \times 6 \text{ (cables)}}{50\,000 \text{ kW}} = 1\cdot375 \text{ per cent loss in 30 miles.}$$

*Note.*—The figure $100 \times 10^{10}$ ohms per $\text{cm}^3$ is too low, and $150 \times 10^{10}$ ohms per $\text{cm}^3$ is more nearly correct.

Comparing this now with the resistivity loss in the 30 000-volt three-core non-concentric cable, we have the following:—

$$\text{Watts per mile} = \frac{2\pi \times E^2 \times (5\,280 \times 30\cdot5)}{\rho_{(av.)} \times 2\cdot3 \times \log_{10}(1\cdot80/1\cdot20)}$$
$$= \frac{6\cdot28 \times (17\,320)^2 \times 5\,280 \times 30\cdot5}{100 \times 10^{10} \times 2\cdot3 \times \log_{10}(1\cdot80/1\cdot20)}$$

Watts per mile per core = 750
Watts per mile per cable = 2 250
Kilowatts per mile per cable = 2·25
Kilowatts per mile (10 cables) = 22·5
Total kilowatts in 30 miles = 675

Hence the percentage loss = 675/50 000 = 1·12 per cent. Hence the difference in leakage conductance loss between the 30 000-volt cable system and the author's 100 000-volt cable system is only one-quarter of 1 per cent.

### Preliminary Calculations for Potential-drops on the Author's System.

The calculations may be greatly simplified—though of course with some loss of accuracy—by assuming that the reactance drop in the line at full load is of the same order as that worked out in Appendix B for a plain single-core cable (per phase), and that the capacity rise at no load is also of about the same order; also that the capacity current required for charging the further half of the line is fed to the substation through the central cores at 100 000 volts, in the manner indicated in Figs. 12 and 14.

We have then merely to see that the copper in the central cores is sufficient to carry the vectorial sum of the charging and load currents at a current density comparable with that obtaining for the load current alone; so that the drops in the two cases (i.e. with and without the load current) remain equal.

Having obtained the drop with the reduced section of copper and without the charging current (i.e. when carrying the "load" current alone), we can add the reactance drop and the capacity rise, taking these at the values given in Appendix B for a plain single-core cable, per phase. The sum of the three terms will represent the "regulation" of the line.

Assuming, then, for the present, that the whole load to be transmitted is divided, half being carried by the three "hexagons" and half by the "major star" (or stars) it will be found that the following is the division of the load current:—

(1) On the cores a and $a_1$ [see Fig. 9 (1)] we have to pass 152 amperes per core, viz. 90 amperes due to the "major star" and 62 amperes due to the "hexagon."

(2) On the cores b and $b_1$ and c and $c_1$ we have to pass only 62 amperes.

Let the central cores a, $a_1$ be worked at a current density of 750 amperes per square inch; let b, $b_1$ be worked at 560 amperes per square inch; and let c, $c_1$ be worked at 750 amperes per square inch.

The voltage-drops in any single wire are then: in a or $a_1$ 1 125 volts; in b or $b_1$ 843 volts; and in c or $c_1$ 1 125 volts.

Expressed as percentage losses these are:—

a and $a_1$ = 1·95 per cent in terms of the "major star,"
= 3·75 per cent in terms of the "hexagons,"
b and $b_1$ = 2·8 per cent in terms of the "hexagons,"
c and $c_1$ = 3·75 per cent in terms of the "hexagons."

The cross-sections are :—

$a$ and $a_1 = 0{\cdot}203$ square inch, each (corrected to $0{\cdot}235$) (see below)
$b$ and $b_1 = 0{\cdot}107$ square inch, each
$c$ and $c_1 = 0{\cdot}08$ square inch, each.

The mean drop on the hexagons $= (3{\cdot}75+2{\cdot}8+3{\cdot}75)/3$,
$= 3{\cdot}43$ per cent.

The mean drop on the major star and on the hexagons combined $= (1{\cdot}95 + 3{\cdot}43)/2$,
$= 2{\cdot}69$ per cent.

This means that at half load (at which point the major star is switched out) the major star at the receiving end would receive :—

$$100 - \tfrac{1}{2}(1{\cdot}95) = 100 - 0{\cdot}97 = 99{\cdot}03 \text{ per cent}$$

of the full voltage of the sending transformer : while the hexagon would receive $100 - \frac{1}{2}(3{\cdot}43) = 98{\cdot}3$ per cent of the voltage of the sending transformer.

The difference between them would thus be 0·7 per cent. This difficulty would be remedied by arranging for different winding ratios at the sending and receiving ends, so as to equalize the percentage drops at, say, three-quarter load, and so that on full load the major star would take too much load and at half load the hexagon would take too much. It might be desirable to have an automatic induction regulator with a very small range, but this is not at present contemplated.

Allowing for the capacity current of the system we must increase the section of the central core in the proportion of $\sqrt{[(152)^2 + (88{\cdot}5)^2]}/152$, i.e. to 0·235 square inch.

Allowing for this, and remembering that, on the occasion of the breakdown of a cable, the " hexagon " belonging to that cable is broken up and that consequently a proportion of the cross-section of the central core corresponding to 62 amperes is liberated and also that 62 amperes is liberated in the intermediate and external cores of the cable, it will be seen that the cable will readily be able to grapple with the situation if the cross-section of the central core be raised to the above figure.

This is substantially the figure that has been the basis of estimates of cost obtained from the cable makers.

The loss in transmission at full load, when averaged over the " major star " and the " hexagons," comes out, as already indicated, at 2·69 per cent.

If to this we add the capacity rise and reactance drop obtained previously (see Appendix B) for a single-core cable, viz. 1·2 per cent and 1·2 per cent respectively, we obtain a total of 5·1 per cent.

It must be remembered that, if the author's deductions are correct as to the practicability of supplying the charging current of the line from the lagging component of the consumers' load, both these " drops " disappear altogether, and the " regulation " of the line then becomes 2·69 per cent, a figure so low that we could afford to reduce greatly—perhaps even to halve—the cross-section of copper in the line, or, alternatively, to double the distance for the same " regulation " as that obtained with a single-core cable system.

We might thus easily transmit up to 50 miles with high efficiency, which means 100 miles when transmitting from both directions, as would be probable in railway work (e.g. between London and Birmingham).

## APPENDIX E.

### Comparative Costs of 30 000-volt and 100 000-volt Schemes.

### Scheme " A " (30 000 Volts).

| | | £ |
|---|---|---|
| *Buildings* .. .. .. .. .. | | 10 000 |
| *Oil switches (including busbars) :* | | |
| 6 three-phase automatic switches, 5 000 volts, each to carry 2 420 amperes and rupture 1 500 000 kVA .. .. .. | £<br>16 000 | |
| 6 three-phase non-automatic switches, 30 000 volts, each to carry and rupture 366 amperes | £<br>10 000 | |
| | | 26 000 |
| *Transformers :* | | |
| 30 4 200-kVA, single-phase, 30 000-volt, 0·8 power factor, 50-period transfomers (including 2 spares) .. .. .. | | 60 000 |
| *Station cables and busbars, etc. :* | | |
| Allow .. .. .. .. .. .. | | 3 000 |
| *Trunk cables :* | £ | |
| Including laying .. .. | 950 000 | |
| Excavating and reinstating streets | 50 000 | |
| | | 1 000 000 |
| Total .. .. .. .. .. | | £1 099 000 |

### Scheme " B " (100 000 Volts).

| | | £ |
|---|---|---|
| *Buildings :* | | |
| (Based upon actual figures) .. .. .. | | 25 000 |
| *Oil switches :* | | |
| 5 000 *volts.* | | |
| 2 three-phase automatic switches, each to carry 3 340 amperes and rupture 1 500 000 kVA .. .. .. | £<br>5 000 | |
| 6 three-phase automatic switches, each to carry 577 amperes and rupture 750 000 kVA .. .. .. | 6 000 | |
| 4 three-phase automatic switches, each to carry 805 amperes and rupture 750 000 kVA .. .. .. | 4 000 | |
| 100 000 *volts.* | | |
| 4 three-phase non-automatic switches, each to carry and interrupt 90 amperes .. .. .. .. | 7 000 | |
| 12 isolating switches, for 200 amperes ; 24 isolating switches, for 100 amperes | 5 000 | |
| 3 earthing switches and isolating switches .. .. .. .. | 2 000 | |
| Sundries .. .. .. .. | 1 000 | |
| | | 30 000 |
| *" Major star " transformers :* | | |
| 8 7 000-kVA, single-phase, 5 000/60 000-volt, 0·7 power factor, transformers. 8 7 000-kVA, single-phase, 2 800/60 000-volt, 0·7 power factor, transformers .. | | 52 800 |

| | | £ |
|---|---|---|
| Brought forward .. .. .. .. | | 107 800 |
| *"Hexagon" transformers:* | | |
| 20 5 000-kVA, 2 800/60 000-volt, 0·7 power factor, single-phase transformers .. .. .. | £<br>50 000 | |
| 6 2 500-kVA, 2 800/30 000-volt, single-phase, transformers .. | 10 000 | 60 000 |

*Note.*—If the substation load be used to feed the capacity current, the above transformer cost will be reduced to, say, £75 000.

| | |
|---|---|
| *Station cables, busbars, etc.:* | |
| Allow .. .. .. .. .. .. | 5 000 |
| *Trunk cables* .. .. .. .. .. | 400 000 |
| TOTAL .. .. .. .. .. | £572 800 |

*Note.*—If the substation load be used to feed the capacity current, the above total cost will be reduced to £535 000.

## APPENDIX F.

The author desires to add the following interesting and, as he judges, important results obtained by Messrs. Clark and Shanklin in connection with the drop in the resistivity of the dielectric as affected by temperature, voltage gradient and frequency. The following figures are taken from some curves plotted by the author and roughly embodying Messrs. Clark and Shanklin's tests:—

| Frequency | Voltage | Cable No. | Potential gradient | Temperature | Resistivity |
|---|---|---|---|---|---|
| ∾ | V | | kV/cm | °C. | |
| 60 | 12 000 | 2 | 15·8 | 24 | $185 \times 10^{10}$ |
| 60 | 12 000 | 2 | 15·8 | 30 | $120 \times 10^{10}$ |
| 60 | 12 000 | 2 | 15·8 | 40 | $53 \times 10^{10}$ |
| 60 | 12,000 | 2 | 15·8 | 50 | $27 \times 10^{10}$ |
| 60 | 12 000 | 2 | 15·8 | 60 | $12 \times 10^{10}$ |
| 60 | 12 000 | 2 | 15·8 | 70 | $8 \times 10^{10}$ |
| 60 | 12 000 | 2 | 15·8 | 80 | $5 \times 10^{10}$ |
| 60 | 12 000 | 2 | 15·8 | 90 | $4 \times 10^{10}$ |
| 60 | 12 000 | 2 | 15·8 | 100 | $2{\cdot}5 \times 10^{10}$ |
| 60 | 48 000 | 1 | 60 | 23 | $38{\cdot}5 \times 10^{10}$ |
| 60 | 48 000 | 1 | 60 | 30 | $25 \times 10^{10}$ |
| 60 | 48 000 | 1 | 60 | 40 | $15 \times 10^{10}$ |
| 60 | 48 000 | 1 | 60 | 50 | $9 \times 10^{10}$ |
| 60 | 48 000 | 1 | 60 | 60 | $5 \times 10^{10}$ |
| 60 | 48 000 | 1 | 60 | 80 | $3 \times 10^{10}$ |

*Note.*—Cable No. 1 had a core radius of 1·5 cm and an insulation radius of 2·53 cm.

Cable No. 2 had a core radius of 1·65 cm and an insulation radius of 2·61 cm.

## APPENDIX G.

### BIBLIOGRAPHY.

RUSSELL, A.: "The Dielectric Strength of Insulating Materials and the Grading of Cables," *Journal I.E.E.*, 1908, vol. 40, p. 6.

OSBORNE, H. S.: "Potential Stresses in Dielectrics," *Transactions of the American Institute of Electrical Engineers*, 1910, vol. 29, pt. 2, p. 1553.

RAYNER, E. H.: "High-voltage Tests and Energy Losses in Insulating Materials," *Journal I.E.E.*, 1912, vol. 49, p. 3.

BEAVER, C. J.: "Cables," *Journal I.E.E.*, 1915, vol. 53, p. 57.

CLARK, W. S., and SHANKLIN, G. B.: "Insulation Characteristics of High-voltage Cables," *Transactions of the American Institute of Electrical Engineers*, 1917, vol. 36, pt. 1, p. 447.

SHANKLIN, G. B., and MATSON, J. J.: "Ionization and Occluded Gases in High-tension Insulation," *ibid.*, 1919, vol. 38, pt. 1, p. 489.

CLARK, W. S., and SHANKLIN, G. B.: "High-tension Single Conductor Cable for Polyphase Systems," *ibid.*, p. 917.

ATKINSON, R. W.: "The Dielectric Field in an Electric Power Cable," *ibid.*, pt. 2, p. 971.

DAVIS, C. W., and SIMONS, D. M.: "Allowable Working Stresses in High-voltage Electric Cables," *Electric Journal*, 1920, vol. 17, p. 292.

FERNIE, F.: "Insulation Experiments," *Beama*, 1921, vol. 9, p. 244.

DAVIS, C. W., and SIMONS, D. M.: "Maximum Allowable Working Voltages in Cables," *Transactions of the American Institute of Electrical Engineers*, 1921, vol. 40, p. 12.

HÖCHSTÄDTER, M.: "Dielectric Losses and Allowable Stresses in High-voltage Cables," *Elektrotechnische Zeitschrift*, 1922, vol. 43, p. 612.

ROPER, D. W.: "Dielectric Losses and Stresses in Relation to Cable Failures," *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 423.

SIMONS, D. M.: "On the Minimum Stress Theory of Cable Breakdowns," *ibid.*, p. 433.

DEL MAR, W. A., and HANSON, C. F.: "Effects of the Composite Structure of Impregnated Paper Insulation on its Electrical Properties," *ibid.*, p. 439.

MIDDLETON, W. I., DAWES, C. L., and DAVIS, E. W.: "Potential Gradient in Cables," *ibid.*, p. 572.

DU BOIS, D.: "The Action and Effect of Moisture in a Dielectric Field," *ibid.*, p. 689.

SHRADER, J. E.: "Corona in Air Spaces in a Dielectric," *ibid.*, p. 702.

Report of the Standards Committee of the American Institute of Electrical Engineers, June 1922: "Rating of Cables in Relation to Voltage."

## DISCUSSION BEFORE THE INSTITUTION, 7 DECEMBER, 1922.

**Mr. C. P. Sparks:** The problem put before us is the straight transmission of 50 000 kW over 30 miles, and the author gives a particular instance of transmission at 30 000 volts with three-core cables versus single-core cables with intersheaths at 100 000 volts. Straight transmission is, as a rule, to make use of natural resources, e.g. water power, or some form of fuel that cannot be transported. In this country we have particularly before us distribution over a wide area, i.e. the building up of a load sufficiently large to justify the use of large power stations, and such distribution requires a system suitable for control at a number of substations. The alternative method of transmission, viz. by means of overhead lines, is not mentioned in the paper, and I feel that straight transmission would have to be carried out by such means rather than by the three-core or the single-core cable proposed. Continuous improvement has been and is being made in cable design. The first 10 000-volt cables were designed by Ferranti and put into use in 1890, the dielectric having a thickness of $\frac{1}{2}$ inch. The next definite step forward was between 1902 and 1903, when a system working at 20 000 volts came into use on the North-East Coast. In 1915 30 000-volt three-core cables were used for transmission in this country, amongst other instances being work carried out by me in South Wales. I expect the discussion will bring out the fact that cable makers are now prepared to build three-core cables and guarantee them not only for 40 000 volts but for still higher pressures. The limiting factor in connection with three-core cables is hysteresis, which was first drawn attention to by Mr. Mordey in 1901 in connection with certain tests which he carried out with me. It was then found that, with the lower pressures of 6 000 and 10 000 volts then in use, hysteresis in cables was unimportant. The question did not arise again until 1915, when the higher pressure of 30 000 volts was adopted. During the past five years cable makers have halved these losses, and at Birmingham the 33 000-volt cables have the same thickness of dielectric as was employed in 1890 for 10 000 volts, i.e. $\frac{1}{2}$ inch. I feel that if the problem of straight transmission at 40 000 volts were before us, it could be solved by the use of five 40 000-volt, three-core cables at half the cost which the author has given for the 30 000-volt cables, without exceeding the practical limits of pressure loss in transmission. As a practical engineer, I require the cable to be armoured. The author says on page 221, "By increasing the amount of copper by 10 per cent, the iron wire loss can probably be compensated for by the reduced copper voltage-drop, and may then be neglected altogether." I want something much more reassuring than that, as I do not consider that it would be wise, from the point of view either of operation or of the safety of the public, to have cables working at the pressure suggested, unless the cables are armoured. On page 230 the author states that with 30 000-volt transmission the loss in transmission with 5 cables would be about 19 per cent, "and the latter regulation is entirely impracticable without a very great outlay in induction regulators and considerable expense in the maintenance of the same." With long lines I think a regulator is entirely justified. It is true that in short transmissions the expense is unwarranted, but I see no reason why, with our present knowledge of regulators, they should not be quite practicable on quite a large scale from the points of view of capital cost, running cost and reliability. In conclusion I feel that where straight transmission is required over a long distance, it should be effected by overhead lines. If, on the other hand, this is not practicable, then three-core armoured cables should be used at 40 000 volts or over.

**Dr. J. A. Fleming:** It is certain that if the electrification of main-line railways is to take place, the subject of transmission at high pressures by underground cables will have to be considered. The problem is fundamentally one of electric strength versus dielectric coefficient or constant. Unfortunately, these two qualities vary, generally speaking, in the same direction. An insulator of high electric strength has, with one exception, a high dielectric constant, the exception being compressed air. The electric strength of such material as is generally used in underground conductors, e.g. impregnated jute or hemp, is usually given at from 200 to 250 kV/cm. The dielectric constant is high, i.e. 3 or $3\frac{1}{2}$; thus the capacity current is large. In the case of air, the electric strength at ordinary pressure is only about 30 kV/cm, but it increases almost proportionately to the pressure, so that if it is pumped up to 100 lb./sq. in. it will have an electric strength of about 200 kV/cm, i.e. approximately equal to that of impregnated jute or hemp. The important point is, however, that the dielectric constant will not increase much above unity, and therefore the capacity current will be about one-third of what it would be on a solid dielectric. Let us suppose that a copper rod is insulated by some suitable form of solid insulator in the axis of a copper tube as the return, and that the two are placed in a steel pipe which is jointed and made tight for a pressure of 150 lb./sq. in., the copper tubes being jointed by copper sleeves. If there were an air space of 1 inch all round the central conductor, the electric strength, at 100 lb./sq. in., should be 400 kV/cm, which would allow an ample margin, and there would be no difficulty in maintaining that pressure against a slight leak at a very small expense. Indeed, a small leak might be an advantage in keeping out moist air and in getting rid of ionized air. The one thing that might be questioned is whether the ionization of air would continue at 100 000 volts to an extent which would break down the insulation; also, whether there are any very serious difficulties in conveying the current through insulated glands into the conductors. I should like to see an experiment of that kind tried on rather a large scale, to find out whether with highly compressed air we could not derive the advantages of high electric strength with a small dielectric constant and, therefore, small capacity currents.

**Mr. C. J. Beaver:** The author has referred to the proposals which I made in 1915 with regard to these intersheath single cables, but I should like to point out that those proposals did not originally emanate solely from me. Some of the suggestions with regard to the subject go back as far as 1906, when the general principle was suggested by Mr. Morris in connection with Dr. Russell's paper.* A considerable amount of work was subsequently done by Dr. Russell, Mr. Ll. B. Atkinson and Mr. A. E. Tanner in scientifically developing the principle of intersheath grading and adapting it to the conditions of commercial use. It has remained for the present author, by means of this six-phase/three-phase system, to combine the principle with a system of distribution in which intersheaths function as current-carrying layers as well as potential distributors. In taking that step he has enormously increased the commercial efficiency of the intersheath type of cable. Apart from questions of the operation of the six-phase/three-phase system, it seems to me that the author's proposals may be regarded as involving two sets of practical problems. The first relates to the production of the necessary transformers and switchgear, and the second to the manufacture and installation of the proposed cable. With regard to the latter, the author's demands on the cable maker in the matter of stress *qua* stress are not at all exorbitant, but the form of cable is somewhat foreign to present-day cable-making practice. I happen to know that the author has, or had, some misgivings as to whether the outer section of the cable shown in Fig. 6 could be made without endangering the efficiency of the inner portions by the heat treatment involved in the impregnation of the outer layer of dielectric. Such a danger undoubtedly exists in the ordinary vacuum or vacuum-pressure method of impregnation, but, as I have pointed out to the author, there is another method by which risks of this character can be entirely avoided. Broadly, this consists in impregnating the paper in sheet form prior to cutting it into strips and applying it to the conductor. This method was evolved by me in 1897, and has been solely used by my company ever since. Obviously, all parts of a dielectric made on this principle must receive the same treatment, whereas this cannot be the case in the ordinary method. Moreover, in the ordinary process the dielectric properties of the impregnating medium—in so far as they are correlated to physical properties—have to be subordinated to the necessity of penetrating the mass of paper under reasonable conditions of time and temperature. Having to be thin and mobile in order to penetrate, a tendency to bleed out again, or to become displaced under working temperature conditions, is entailed. In addition, there is always the risk of insufficient penetration on the one hand, or too prolonged exposure to the high temperature of the impregnating process on the other. The "prior" impregnating process is entirely free from these disadvantages, allows considerably greater freedom in the choice of materials, and consequently permits much more scope in securing the best combination of physical and electrical properties in the impregnating medium. The desirability of this method becomes, of course, greater as higher voltages and consequently greater thicknesses of dielectric have to be dealt with. The author's reference to the work of Clark and Shanklin and others brings up the important subject of the effect on dielectric losses of the occlusion of air and gases. These investigators attached so much importance to this matter as to conclude that the critical stress at which occluded air becomes ionized—about 19·5 kV/cm—should not be exceeded in an impregnated paper dielectric. British cable makers, however, did not accept this dictum, and to-day more than one firm, including my own, can point to cases of two years or more of satisfactory working at stresses up to 50 kV/cm. There appears to be little doubt, however, that freedom from occluded air and gases would give considerable advantage not only with regard to dielectric loss, but probably also to electric strength. The "prior" impregnation method gives freedom from occluded gases because there is no heat treatment after the dielectric is built up. With regard to occluded air, I do not think that either process has yet produced an absolutely air-free dielectric, although certain refinements are employed to that end in each. It will be fairly clear, however, on a moment's consideration, that if, in the "prior" method, the already impregnated paper strips could be applied to the cable in an air-free medium, e.g. under the surface of very viscous oil or molten compound, the dielectric so built up could not contain air. The necessary plant to accomplish this has been designed and constructed and will shortly be in use.

**Mr. P. V. Hunter:** It seems to me that, up to the present, cable manufacture and research and development on cables in this country have proceeded on quite fixed and well-defined lines. Certain definite forms of cable have been stereotyped, and the direction of progress has been to try to increase the specific loading of the materials. For instance, the question of the current density at which cables can be run has during the past 10 years received very considerable attention, and the stress at which the dielectric can be operated has received if anything even more attention. This has resulted in considerable progress, but in one direction only. Now the author has entirely ignored all this line of progress and has set himself quite different ideals. It would therefore be hardly fair to criticize the paper for not dealing with this aspect of development. I should like to say, however, that he has not done the cable manufacturer of this country anything like justice in the 33 000-volt cable which he has shown on page 232 for the purpose of comparison with his own proposals. It must be remembered that the author's proposal is, after all, very speculative. If, therefore, he has put up a speculative proposal he ought to compare it with something of a similarly advanced nature in existing methods, and I think I shall be quite safe in saying that a 66 000-volt three-core cable run at $2\frac{1}{2}$ times the current density that is proposed in the paper for the 33 000-volt cable would be a great deal less speculative than the cable and method of operation proposed by the author. Had he made his comparisons on this basis the saving of £500 000 would, of course, have completely disappeared. I think that the author's proposals really amount to this: "I will put a stop to any attempts to increase the specific loading of my materials, and I will see whether by changing my circuit arrangements or by any kind of subterfuge I can gain advantages in other directions." He has no doubt been encouraged in this line of attack by the fact that in communication circuits there have been very great advances in dealing with the development in this way. Mr. Gill in his Inaugural Address told us how many long-distance communication circuits were operated on four wires. The number appears almost incredible to a power engineer unfamiliar with such matters, and I think that the present author has set himself to discover whether or not it is possible to arrive at some similar kind of development in power work. I do not think for a moment that the particular schemes which the author has proposed are in the slightest degree practicable. Mr. Sparks has pointed out that, as described, the scheme proposed would appear to be suitable only for straight end-to-end transmission. I do not think any scheme which is limited in that way would be at all applicable to the conditions of this country. On the other hand, if an attempt is made to apply this scheme to any kind of high-pressure interconnected distribution network, the amount of switching entailed will be excessive. For instance, the number of busbars required in a substation where there is a junction between three such feeders as are shown in Fig. 11 would, I think, be 21. To make the scheme at all practicable the serious difficulty of capacity current which the author has encountered has to be overcome. This difficulty is met with on all occasions when one tries to limit the maximum stress on the dielectric and employ it more usefully by running at a constant stress throughout. This means, in the case of single-core cables, or cables of similar construction, that the large mass of dielectric near the outer periphery has to have its stress increased. The result is a large increase in capacity current. The author's proposed scheme of neutralizing the capacity current and running at unity power factor should not be credited as an advantage of his system. It is an essential complication which must be adopted because he is running into the difficulty of greatly increased capacity current. As he has to attack this difficulty it is very natural that he should attempt to eliminate the capacity current entirely, and with this I agree. Fig. 11, I understand, gives in diagrammatic form the essence of the author's specific proposals. I am not sure that it is easy to follow from the description what is intended and the reasons which have led the author to the arrangement shown, and it may be of interest to state briefly the genesis of the arrangement as it appears to me. The author has chosen a main transmission pressure so high that some form of single-core cable is necessary. In order to keep the dielectric stress within the limits postulated he has had to assume the use of intersheaths regulating the pressures between sections of the dielectric. These intersheaths must necessarily carry large capacity currents and, with a view to increasing the amount of energy transmitted by the arrangement, and also no doubt having in mind that the addition of capacity currents and energy currents gives a resultant of less magnitude than the arithmetical sum, he has endeavoured to arrange that the intersheath shall also carry energy current. It would be almost ideal for his purpose if the energy current to be carried by the intersheaths could have been the ordinary three-phase system, but unfortunately this is not very suitable. The result has been that the author has had to employ a six-phase arrangement for superimposing on his intersheaths, and this has led to the employment not only of the hexagon arrangement but also of six cables instead of three, which would otherwise have been satisfactory. On the whole, therefore, it is fair to state that the main object of the whole of the arrangement is to employ intersheaths for the purpose of transmitting energy, as well as capacity currents.

---

* "The Dielectric Strength of Insulating Materials, and the Grading of Cables," *Journal I.E.E.*, 1908, vol. 40, p. 6.

*Communicated:* It is well that attention should be directed to the author's argument for employing an excess of cables in order to save energy losses. The author computes that a 1 per cent saving in energy lost is equivalent to £58 300 in capital expenditure. The cost of a unit of losses is assumed to be 0·5d., the period on which the computation is based being 16 years. This computation obviously assumes that for the next 16 years there will be no reduction in the cost of producing electricity, which seems to me to be very improbable indeed. If, however, there is a reduction in the cost of producing electricity, then the capital value of the losses falls, and I have no hesitation in predicting that during the next 16 years the cost of the losses will be very substantially less than the figure stated by the author, with the result that any capital expended on the assumption that it paid to spend capital to save losses would be largely wasted. Apart, however, from this weakness in the author's argument, the whole suggestion that supply authorities should spend capital purely for the purpose of saving losses is against all commercial practice. In the author's case he proposes to run his 33 000-volt cable at a current density of 500 amperes per sq. in., when a density of at least 1 250 amperes per sq. in. would be permissible. In other words, although four cables would be sufficient for his purpose he proposes to put in ten, merely because he can show on paper that the saving in losses would justify the extra capital expenditure. This argument seems to me to find no support in practice in this or any other country, nor is it likely to appeal to any branch of the industry with the possible exception of that which makes the cables.

**Mr. J. S. Highfield:** A study of the paper seems to suggest that the author is adding to the well-known complication of transmitting electricity by alternating currents; and it makes one feel all the more that if, for the sake of simplicity, we could generate and transform direct current, the whole problem would become much more simple. On that subject the author suggests that even if we could use direct current there would still be this difficulty of intersheaths in order to make the insulation secure. I can assure him that up to 100 000 volts there is no difficulty at all in using a single-core cable with $\frac{1}{2}$ in. of insulation (or perhaps a little more) to work at 100 000 volts. For some years there has been a cable supplying Lyons at that pressure. I laid a main consisting of two single-core cables of 0·125 sq. in. cores plain lead-covered and laid in iron pipes, for the Metropolitan Electric Supply Company, to work at 100 000 volts. Dr. Fleming has referred to the use of compressed air as an insulator. He may be interested to hear that some years ago, when I was working a great deal on the possible use of direct current for high-tension transmission, it became obvious that it was much easier to make a compressed-air cable with one core than with three. With one core it appeared to be sufficiently easy to be worth trying. In fact we laid down a good many lengths of 18 ft. steel tube with an insulator on each joint, and drew through these insulators a stranded cable of about $\frac{1}{4}$ sq. in. section. We drew it up tight so that it could not touch the tubes. It was quite easy to go round corners because there was a suitable insulator at each joint. Working at a pressure from 100 to 120 lb./sq. in. there was no difficulty in applying an alternating current of 60 000 volts between the conductors and the outside of the tube, the diameter of which was, I think, 4 in. In common with Mr. Hunter, I have experienced some difficulty in understanding in what the proposed new system consists, and I do not quite agree with Mr. Hunter's interpretation. Mr. Hunter has discussed Fig. 11 as though an essential part of the system were six cables and a large bunch of transformers. I think that the author could carry out his system perfectly well with one three-phase/six-phase transformer and two three-core concentric cables. His connections are, I think, designed with the idea of keeping two of the neighbouring phases as near earth potential as possible, i.e. about 15 000 volts; the two highest phases within about 90 000 volts; and the two middle ones within about 60 000 volts. Consequently the system might consist in a single transformer providing six phases and two three-core concentric cables.

**Mr. P. Dunsheath:** There are many points in the paper with which I either do not agree or on which I am unable to follow the author's argument. I think that in dealing with certain fundamental principles the author has made one or two slips. One matter to which I should like to call particular attention appears on page 223. Assuming the power factor of the dielectric to be 1·5 per cent, the author calculates the dielectric losses in the usual way, but calls them hysteresis losses, and shows them as hysteresis losses in Fig. 3. That, in my opinion, is not correct. The product of power factor, pressure and charging current gives the total dielectric loss including the conductance losses, which the author refers to as a separate item in the lower part of col. 1, page 223. Turning now to the author's six-phase/three-phase system, apparently he employs six cables as detailed in Fig. 6, and by applying 30 000 volts between the inner conductor and the first intersheath, another 30 000 volts between the first and second intersheath, and 18 000 volts between the latter and the lead, he is able to work a 100 000-volt three-phase system. It seems to me that the best way to criticize the system is to compare it with a straightforward tapping system, using exactly the same cable with the same voltage between conductors. In Fig. A I have shown the elements of the author's system on the left-hand side and the equivalent simple tapping system on the right-hand side. It is obvious from the vector diagram that the addition of the vector voltages is considerably less with the author's system than with the simple tapping system. As a matter of fact, with equal stresses on the dielectrics of two equal-sized cables the voltage available on the left-hand system is 58 000 and on the right-hand system 78 000. It seems to me that this is really the basic principle of the matter, and to condense my point I should like to ask the author what are the advantages of his system over that shown in Fig. B. Here two, four or six cables constructed similarly to that of Fig. 6, *but only up to the first lead sheath*, i.e. 4·02 cm radius, are used instead of an equal number of cables in accordance with Fig. 6, with a radius of 5·12 cm. With the alternative which I propose, six cables, much smaller than the author's, will carry the same voltage, i.e. 100 000 volts three phase, without the complication of any six-phase hexagons and without the loss, so far as I can see, of a single advantage claimed for the six-phase system. On the question of carrying load current in the intersheaths, the author implies that this is one of the advantages of his system. Now this advantage can be claimed for any intersheath system, but is it such an advantage, after all? At first sight it seems to be a very attractive proposition,

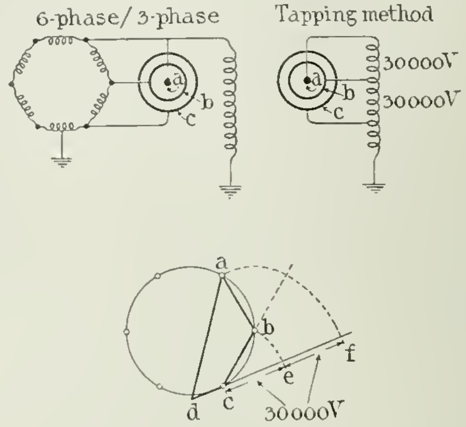


FIG. A.

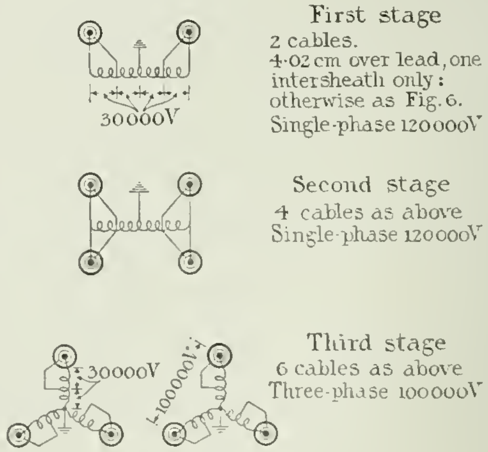


FIG. B.

but when it is remembered that energy carried at the top voltage in the main conductor requires much less current than if carried in an intersheath, the advantages are not so obvious. In passing, I should like to state that the author is not the first to propose the use of intersheaths for carrying current. The firm with which I am connected hold a patent * for doing the same thing on a simple tapping system. So far my criticism has been of the author's method of using intersheaths, but I should like to say a word on intersheaths in general. The development of super-pressure cables by the use of graded potential intersheaths has been very much discussed, but I do not think they are as effective as they are generally considered to be. I know that many authorities hold that a cable breaks down at a certain maximum stress and that, by a re-distribution of stress by potential sheaths, higher values will be obtained for the breakdown of a given total thickness of dielectric. I am sure that when we know more about this subject we shall find this to be absolutely untrue. A cable does not break down when a certain maximum stress is reached, but for some other reason. I know that makers of condenser-type terminals are quite convinced of the usefulness of intersheaths, but I am of the opinion that if intersheaths do improve a dielectric they do so by re-distributing the heat, and possibly stress, circumferentially rather than by re-distributing the stress radially, and that if an intersheath cable were left without the ends connected to transformer tappings the results would be quite as good as if they were connected. It is largely because of these views on the uselessness of potential grading that I have been working during the past few years along the lines of developing super-pressure cables, using three-core cables, and I find that it is practicable to transmit the power required for the case quoted by the author, i.e. 50 000 kW, over three three-core cables having an overall diameter of 4·5 inches. The cable may be either plain three-core or of the type which I prefer, shown in Fig. C, which I will refer to as the S.L. type, as the cores are each separately lead-covered. The objection to the use of single-core cables is very frequently based on the impossibility of armouring, but here is a type in which the armouring is easily employed and which has many other advantages, both mechanical and electrical. As it may be objected against my suggested alternative to the author's system that the losses will be more, I have tabulated various values, from which it will be seen that the advantage is all with the three-core type. The S.L. type has somewhat larger losses than the plain three-core cable, but its many other advantages, e.g. flexibility, uniformity of temperature, etc., more than compensate for these. As regards cost, I estimate that the saving of £500 000 shown by the author by using his system could be increased to about £550 000 by using three three-core cables as suggested. The figures in the following table are obtained from a long series of tests recently carried out and still in progress on two lengths of 60 000-volt, three-core cables, samples of which I have placed on the table for inspection.

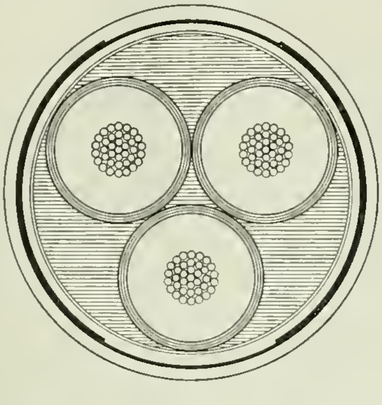


FIG. C.—"S.L." type of 60 000-volt, three-core cable. Conductor 0·23 sq. in. (37/0·090); overall diameter 4·5 in. (Henley).

*Comparison of Six-phase/Three-phase Transmission at* 100 kV *with Simple Three-phase Transmission at* 60 kV.

| | 6-phase/3-phase: 100 kV | Simple 3-phase: 60 kV | |
|---|---|---|---|
| | Using 6 concentric cables | Using 3 plain 3-core cables | Using 3 S.L. type 3-core cables |
| Distance .. | 30 miles | 30 miles | 30 miles |
| Regulation .. | 5 % | 5 % | 5 % |
| Charging kVA per phase | 20 460 | 8 750 | 10 300 |
| Copper losses at full load, in kW | 1 387 | 2 023 | 2 023 |
| Sheath losses at full load, in kW | ? (take = 0) | ? (take = 0) | 202 |
| Copper and sheath losses, in kW | 1 387 | 2 023 | 2 225 |
| Ditto per annum, in units, 40% load factor | 1 940 000 | 2 840 000 | 3 120 000 |
| Dielectric loss at full load, in kW. | 918 | 394 | 463 |
| Dielectric loss per annum in units, 24 hours' load | 8 050 000 | 3 460 000 | 4 060 000 |
| Total loss per annum, in units | 9 990 000 | 6 300 000 | 7 180 000 |

**Dr. W. Cramp:** In the first place, the use of single-core, lead-covered cables for alternating currents is, to my mind, now a thing of absolute certainty. It is perfectly safe to use them even for periodicities higher than 50. I am in possession of figures which show that the loss which the author has allowed in the lead is really in excess of what he is likely to meet with in practice. I would go further and reassure

---

* British Patent 138 377.

Mr. Sparks to this extent—that experiments which are now being carried out at Birmingham seem to show that even in a single-core *armoured* cable the loss is much less than is generally anticipated. The second point is that cable makers who have used intersheaths, and who propose to use them, seem to me to be omitting one important theoretical possibility. It is well-known that if a conductor and a partial conductor carry a current such as this capacity current, a charge will collect at the junction between them, and will disappear directly the current disappears. If the capacity current has to pass through the metal sheath—that is to say, if the current on the two sides is virtually the same, so that the capacity current travels from core to core—there will be a charge on each side of the metal sheath, and it may be of very considerable magnitude, in fact sufficient, if there are spaces between the wires, as in the author's rings, to set up an ozonizing discharge. In any case there is the possibility of breakdown near an intersheath due to that cause.

**Mr. A. M. Taylor** (*in reply*): It would seem to be true that, as the *Electrician* remarks, I have not done myself justice in the presentation of the facts which are enunciated in the paper. I will try to remedy this in the reply to the discussion.

The essential points which can be deduced from the data given and on which the paper will stand or fall are the following:—

(1) By employing intersheaths in the manner outlined a gain of roughly 100 per cent in the voltage applied can be obtained for a given depth of insulation.

(2) This enables either the current density in the central copper core to be kept constant while the core section is halved, or alternatively (and this is what I use in my calculations later) the current density to be doubled while the cross-section is reduced to one-quarter.

In the first case half the heat is liberated per foot of cable, and consequently, for two single-core cables of similar thermal constants (one at 55 000 V, non-intersheathed, and the other at 110 000 V, intersheathed) the thermal gradient is halved, i.e. the temperature-rise of the copper is halved.

(3) In the transition from a three-core non-intersheathed cable to a single-core intersheathed cable there is a gain in the thermal gradient—i.e. a reduction in the copper-core temperature-rise—of some 60 per cent, due largely to there being the heat losses of three cores concentrated in the one cable, and in the other that of one core only.

(4) The resistivity gain, due to the reduced temperature of the central core, would of itself be very valuable; but in the case of intersheath cables worked under my proposals the additional gain, due to putting those parts of the dielectric which have to work under the highest dielectric stress at a part of the cable where the temperature is lowest, is very great and would amply compensate for any moderate loss due to increased capacity current. Incidentally, it should also permit of working at much higher voltage gradients, and hence of still further increasing the transmission voltage.

(5) By the method of working proposed, the capacity current at light loads is reduced to one-third of that at full load.

(6) The increase in the total capacity from core to lead sheath (apart from temperature questions), due to the introduction of intersheaths and consequent slight increase in diameter of cable, is almost negligible. In a case which I have worked out it is only 5 per cent.

(7) Above a certain temperature, easily reached in practice, the "leakage conductance loss" (which depends directly on the resistivity) increases very rapidly and outweighs the loss due to increased "permittivity" (i.e. the extra capacity current loss), besides ultimately causing the breakdown of the cable.

In view of the fact that, in the near future, transmissions of a magnitude now only hinted at will certainly be undertaken, and that it is impossible to keep on indefinitely increasing the potential gradient in three-core cables to meet the new conditions, it is advisable—and will assist true progress meanwhile—to consider *now* how these transmissions are to be undertaken. The present paper was written with this object.

Replying now in detail to the discussion on the paper, the most serious criticism is, I take it, that the work can equally efficiently be done with, say, five 55 000-V three-core cables. But those who make this criticism have surely overlooked the supreme importance of temperature considerations. E.H.T. trunk cables may, in emergency, be called upon to carry loads far in excess of their normal loading, and this may occur in the summer time. To neglect this possibility would be suicidal. It is also surely of some importance that an unnecessary £50 000 to £75 000 should not be incurred in regulators, which lose (in boosting by some 20 per cent) from $\frac{1}{2}$ per cent to perhaps $\frac{3}{4}$ per cent of the whole power of the system. I propose to attack the problem from the point of view of temperature of the dielectric. It is rather interesting that the latest important contributor to this question, Dr. Karl Willy Wagner,* emphasizes the drop in resistivity due to temperature as being of supreme importance and the probable initial cause of all breakdowns. The curves which I exhibited as a lantern slide show most conclusively the importance of this question of the leakage conductance loss; also, how remarkably the resistivity itself, for a given ambient temperature, depends on the potential gradient. In the paper I have done my own proposals an injustice by designing a cable such that the present methods of impregnation could be applied to it. As, however, there is a reasonable probability of our being able almost immediately to obtain cables in which (apart from the question of bending, which can be dealt with by larger drums and other precautions) it is immaterial whether the maximum potential gradient occurs at the surface of the central core or on one of the intersheaths, I will take advantage of the gains which my proposals really involve, were such a cable immediately forthcoming. Even if, however, I had to fall back on the cable shown in Fig. 6 of the paper, my conclusions would not be seriously affected.

---

* *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 1034.

A careful examination of Tables 2 and 3 will show that, for practically no more loss than in Table 2, an advantage of 50 per cent in the maximum potential gradient applied to the innermost core (i.e. the hottest —at time of full load) is obtained, as compared with the gradient of Table 2; also that, in Table 2 itself, an advantage of 47 per cent over Table 1 (ordinary non-intersheath) is obtained in the E.M.F. absorbed for a given thickness of dielectric. An advantage of $1 \cdot 47 \times 1 \cdot 50 = 2 \cdot 2$ is thus obtained in the E.M.F. that can be applied to an intersheath cable, for an equal thickness of dielectric—i.e. we may apply 2·2 times the E.M.F. of transmission for a given maximum potential gradient next the central core. Unfortunately, however, this has, in the six-phase/three-phase system, to be discounted by 15 per cent on account of the obliquity of vectors. This brings the gain down to $2 \cdot 2 \times 0 \cdot 85 = 1 \cdot 87$ times; which, however, is only $6\frac{1}{2}$ per cent short of twice. In view of the fact that I am going to compare a 55 000-V three-core non-concentric cable with a single-core 110 000-V intersheath cable having nearly an inch less diameter under the lead sheath (representing a "gift" of very much more than the aforesaid $6\frac{1}{2}$ per cent) it will doubtless be conceded as reasonable that, for a round figure, the above gain in voltage be taken as 100 per cent—not to mention further gains which I might have drawn upon. The three-core cable chosen for the purpose of examining thermal gradient is a standard cable having 1·25 cm thickness of insulation both on conductor and on belt and measuring 10·9 cm over the insulation, in which the maximum potential gradient is 40 kV/cm, the cross-section per core being 0·15 sq. in. The maximum potential gradient is calculated according to Atkinson's method,* which, I believe, is generally accepted as being more accurate than the ordinary method. The internal diameter of the lead sheath is 10·9 cm, as compared with 8·2 cm † for the single-core cable. Had the larger diameter been reduced to 8·2 cm the effect on the maximum voltage gradient of the 55 000-V cable would have been very serious.

Prior to giving detailed consideration to the three-core non-concentric cable, let us first compare two single-core cables—one (intersheathed) for 110 000 V and one (plain) for 55 000 V. It has just been shown that the voltage may be doubled for equal thickness of insulation where intersheaths are employed (single-core cables being considered); let us, then, examine what the doubling of the voltage gives us and, for the sake of simplicity, ignore capacity current:—

(1) Half the load current is required.
(2) The percentage drop may be kept constant.
(3) The copper cross-section per phase (in the 110 000-V cable) is reduced to one-quarter.
(4) The current density is doubled.

Now, to fix ideas, take the 110 000-V cable of Fig. 1 of the paper, of which the cross-section of copper is 0·185 sq. in. The cross-section per phase (2 cables are in parallel per phase; see Appendix B) = 0·37 sq. in. Hence:—

(5) Copper section per phase on 55 000-V cable = 0·37 sq. in. × 4 (as deduced above) = 1·48 sq. in.
(6) No. of cores required in parallel $= \dfrac{1 \cdot 48 \text{ sq. in.}}{0 \cdot 15 \text{ sq. in.}}$ (see Note below)
= 10 cores (per phase).
= 30 single-core cables (per 3 phases).

*Note.*—We cannot put more than 0·15 sq. in. into the three-core cable about to be considered without exceeding the potential gradient of 40 kV/cm.

Now consider that these 30 cables are to be replaced by 10 three-core (55 000 V) cables, and compare the heating in the two cases.

The total heat generated per phase in the 110 000-V cables is obtained as follows, bearing in mind that 2 cables are in parallel per phase on the 110 000-V system, and 10 cables on the 55 000-V system. It is simpler to compare 5 cables of one system with the one cable of the other system; so let us work it out this way:—

The current density on the one 0·185 sq. in. cable works out at approximately 1 000 A per sq. in. (see Appendix B). Hence, from the conclusion already arrived at,

Current density in 55 000-V 0·15 sq. in. cable = 500 A per sq. in.

Now

1 (50 000 V) core at 500 A per sq. in. and of 0·15 sq. in. section represents $X$ watts per ft.

also

1 (110 000 V) core at 1 000 A per sq. in. and of 0·185 sq. in. section represents $4X \times \dfrac{0 \cdot 1}{0 \cdot 150}$ watts per ft.

and

3 (50 000 V) cores at 500 A per sq. in., each of 0·15 sq. in. section, represent $3X$ watts per ft.

But the thermal resistance of the 0·15 sq. in. three-core cable is 95·5 and that of the 0·185 sq. in. single-core cable is 82·5.

(The above thermal resistances are as determined by well-accepted methods.)

Hence the thermal gradient of the 110 000-V cable in terms of the 55 000-V cable is:

$$\frac{4}{3} \times \frac{0 \cdot 185}{0 \cdot 150} \times \frac{82 \cdot 5}{95 \cdot 0} = 1 \cdot 42 \text{ times.}$$

This, however, is for 10 cables in parallel and for 500 A per sq. in.

If we work at higher current densities and with fewer cables in parallel (and greater percentage loss) we get the following results:—

The 110 000-V cable is 1·42 times hotter, when we have ten 0·15 sq. in. three-core cables.
The 110 000-V cable is 0·91 times as hot, when we have eight 0·15 sq. in. three-core cables.

---

* *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 971.
† Based on Fig 1, but modified for 40 000 V/cm.

The 110 000-V cable is 0·51 times as hot, when we have six 0·15 sq. in. three-core cables.
The 110 000-V cable is 0·22 times as hot, when we have four 0·15 sq. in. three-core cables.

So that, with even 8 cables, there is a gain of 9 per cent to be credited to the single-core intersheathed scheme, neglecting altogether the additional advantage that the dissipation of part of the (copper) heat nearer to the outside of the cable gives us. It may be pointed out that an easy calculation shows that the effect of adding intersheaths to a non-intersheath cable is to reduce the thermal gradient (in the proportion of 78·9/82·5 in the case of Fig. 1) rather than increase it, as one might possibly imagine. If only 4 cables were chosen (equivalent to Mr. Sparks's 5 cables at 40 000 V) the 2·5 per cent line drop taken in Appendix B becomes 5·0 per cent, involving 2½ per cent additional loss in the 55 000-V scheme, which, as I have shown elsewhere, is equivalent to £194 000 when capitalized; *besides the fact that the innermost insulation is no less than* 4 *times hotter;* which factors must work to the ultimate destruction of the cable.*

It only remains to add that my calculations are all on a common basis as regards maximum potential gradient. Mr. Dunsheath's figures, and probably also Mr. Hunter's, are vitiated by the fact that they are based on 50 000 V/cm; just 25 per cent more than mine. It may therefore be taken that 8 cables are necessary for 50 000 kW and 16 cables for 100 000 kW against 6 cables with the six-phase/three-phase system, a saving of 10 cables in the latter case (or, say, £750 000).

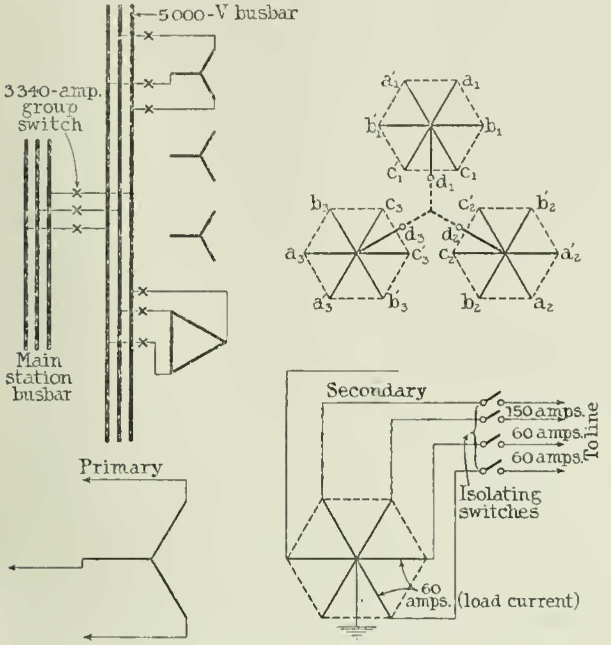
Before leaving the subject of the number of cables it is as well to remark that all my comparisons in the paper are on the basis of maximum potential gradient. I am quite familiar with the fact that this has been challenged as a criterion of the breakdown strength, and I have carefully followed all that has been written on the subject during the last 2 years. As far as I can judge, Mr. D. M. Simons's paper before the American Institute of Electrical Engineers † is the most complete investigation on the subject and his conclusion that, although the maximum potential gradient may not determine the immediate breakdown of the insulation when under test, yet nevertheless it probably determines the ultimate breakdown after a lapse of time, is one with which I fully agree. Although no actual breakdown or deterioration of the insulation next to the central core may be visible on opening up the cable, yet it is undeniable that the atomic stresses must be greater where the potential gradient is greater (with greater hysteresis loss and consequent heating), and it is also undeniable that the potential gradients follow the laws predicated of them, in a uniform dielectric.

Mr. Hunter has challenged the soundness of paying too serious attention to the cost of energy wasted in the cable, and he suggests that the figure of 0·5d. (as an *average* figure) which I have taken for the cost of energy delivered, on only a 40 per cent load factor basis, at a substation 30 miles away, is too high. Surely Mr. Hunter must know that the official life of a high-tension cable is not 16 years, but 25 years; and if I were to reduce the above 0·5d. to 0·33d. (involving a *minimum* figure of 0·16d.) and still were to say that 1 per cent of lost energy meant £78 000, would he be sufficiently optimistic to say that 0·33d. was too high, considering the load factor and the point of delivery? Does he suggest that central station engineers are wrong when they consider carefully the last 1 per cent of the guaranteed efficiency of the plant in determining the tenders? Mr. Hunter is apparently very much alarmed by the amount of capacity current taken by my proposals, and the consequent energy wasted in dielectric loss. I may say at once that I anticipate that the capacity current will be some 80 per cent greater than with an ordinary type of three-core cable. The energy loss due to this will not, at the most, be more than an additional 0·8 per cent of the total power transmitted. Really the total loss will be *less than half the full-load loss,* because of my method of working the transformers and lines in sections. Perhaps he has overlooked the fact that at higher voltages one is bound to get greater capacity current than at low voltages, and if he can ever work up to 100 000 V with three-core cables he will find just the same troubles staring him in the face. I, on the other hand, am equally interested about the conductance losses in Mr. Hunter's cable, owing to the high temperatures of the dielectric, particularly in view of the calculations given on page 236, which show that, even assuming in both cases a comparatively cold dielectric, there is only a difference of 0·25 per cent between the loss with my cable at 100 000 V and a 30 000-V three-core cable. Had I made allowance for the hotter dielectric in his cable, the loss would probably have been much higher. The hotter dielectric, as already pointed out, also affects the permittivity, and consequently the capacity current. Mr. Hunter has arrived at the conclusion that my scheme is not in the slightest degree practicable. I submit that such a wholesale condemnation without any definite specification of the reason is unfair to the author. I presume that he condemns it on account of the alleged complexity of the transformer arrangements. This is merely because they are new to him, and, no doubt, in particular the superposed "major star" arrangement has frightened him. It may relieve Mr. Hunter's mind to know that the scheme can be equally well carried out, and the voltage of transmission still maintained, without any "major star" at all. The system then simply becomes, at the step-up end, three ordinary transformers having the secondaries coupled in double star, which is no more complicated than is used daily in conjunction with rotary converters. Fig. D shows these new conditions. As regards the alleged complexity of the switching, I do not propose to do any automatic switching on the high-tension side, and if possible no non-automatic, except at times of light load. I believe, from a careful study of the experiments carried out by Steinmetz and others, that we should be simply inviting trouble by having automatic switching on the high-tension side with long lines of underground cables. Time will prove whether I am right or not in this prediction. With regard to the suggestion that I should not be allowed to credit my scheme with the neutralizing of the capacity current and running at unity power factor, I have already dealt with this at some length, and if Mr. Hunter will refer to the calculations for a single-core non-intersheath cable at 100 000 V, as given in Appendix B of the paper, and will compare them with the calculations for my own cable, given in Appendix D, he will find that the total kVA under the two schemes is almost identical, which is a sufficient answer to his statement that I have a "greatly" increased capacity current.

---

* Had the first case, alluded to at the commencement of this reply, been taken, the argument in favour of cooler cables could have been made very much stronger. In fact, the core temperature would have come out 10 *times* higher, with 4 cables, than with the 100 000-V system.

† *Journal of the American Institute of Electrical Engineers,* 1922, vol. 41, p. 433.



One hexagon considered separately

FIG. D.—Switchgear arrangement at sending station.

NOTE:—The dotted lines between points $d_1$, $d_2$ and $d_3$, represent conductors of no resistance.

Mr. Sparks has implied that the cost of a five-cable transmission at 40 000 V would be only half that of the cables in the six-phase/three-phase system, and he must surely be very seriously in error. The prices given in Appendix E of the paper for ten 30 000-V cables were the results of estimates from several of the leading cable makers and were compared by me with prices of actual cables then in my possession.

Now the cost of a three-core 0·15 sq. in. cable for 55 000 V will not be appreciably less than that of a three-core 0·25 sq. in. 30 000-V cable, except for the value of the copper saved. (There will in fact be more lead, owing to the greater diameter consequent upon the higher insulation required.) The figures given for the latter cable, including joints and laying, were of the order of £95 000 per cable per 30 miles. Knocking off £12 000 for the reduced copper (including the profit on the same) the price reduces to £83 000 per cable. Now the price per multi-core concentric 100 000-V cable given in my table is only £66 000 per 30 miles, hence Mr. Sparks wants us to believe that his three-core 40 000-V cable will cost only £33 000 per 30 miles. There is a big jump between £83 000 and £33 000 and it is not likely that the cable makers, who simultaneously gave prices for the two systems and knew that they were going to be compared, would make out the worst case that they could for their normal construction of cable. On the question of armouring I can assure Mr. Sparks that the armouring of the cables can be dealt with for less energy than he proposes to lose in his regulators. I expect a great deal less from calculations based on Dr. Whitehead's experiments and Steinmetz's figures, and Dr. Cramp seems to be of the same opinion. As regards a "straight" transmission, I submit that in the ordinary course of things the 100 000 V would only be required for a point-to-point transmission, but that where tappings off such a line took place it would be quite practicable to step down to, say, 30 000 V (or lower) and to carry out ordinary three-phase distribution from the tap-point in each district; and the change from six-phase to three-phase is easy, simple and reliable. If, however, such a step-down is not required at the tapping point, a plain "connection substation," which would be quite cheap, could be used. Mr. Sparks gives it as his view that overhead transmissions will be largely employed for all point-to-point distribution over long distances in this country. I believe, on the contrary, that with the continued use and development of aviation on a big scale there will be great danger in fogs from aeroplanes colliding with overhead lines, in many cases bringing down the latter, not to mention disastrous results to those in the aeroplane. Moreover, the cost of overhead transmission is not at all so low as Mr. Sparks imagines. Where two lines of towers are required, which I suggest is only reasonable on very important transmissions, and upon which I believe even our American friends have decided for such transmissions, the difficulty in obtaining wayleaves for these lines of towers across country will be quite considerable, and some compensation will also be necessary for the strip of land between tower and tower which is threatened by falling wires. The cost per kVA per mile for a 100 000-kW transmission on the lines I am recommending would only be of the order of £0·18, and I remember not so long since analysing an important American estimate for overhead transmission in which (if my memory serves me right) it worked out to something like £0·2 per kVA per mile; so that on such a transmission the cost with underground cables would be as cheap as with overhead, and enormously more reliable.

With regard to Mr. Highfield's remarks, I gather that the area of the 100 000-volt d.c. main to which he alludes would be only 0·125 sq. in. and that the cable would really be working under only 50 000 volts between any part of the core and earth. It would be interesting to know whether this cable has ever been used to carry, say, 150 amperes in the hottest part of the year for several hours, or whether it is merely run at a low current density. No doubt Mr. Highfield is aware that it has been known for some time that, with cables in which the ratio $d/D$ is of the order of 0·3 (which obtains in the present case), values of the maximum potential gradient greatly exceeding standard values have been observed before breakdown occurs—I believe in some cases very greatly in excess of the 75 000 V/cm which obtains in the present case. On the other hand, it is generally accepted that a given d.c. stress is equal in breakdown effect to a very much greater a.c. stress. As regards Mr. Highfield's comments on my transformer arrangements, he is quite correct in saying that I could carry out my system perfectly well with one three-phase/six-phase transformer and two three-core concentric cables. But I think he has overlooked the fact that this arrangement would not permit cf 60 000 volts being exceeded without also exceeding the maximum potential gradient of 40 kV/cm, whereas the repetition of the arrangement, in the manner proposed in Fig. 11, permits of $\sqrt{3}$ times this voltage being employed, which of course gives a very great gain.

Mr. Dunsheath exhibited a lantern slide (Fig. B) showing a diagram of connections which he suggested would give the same results as my proposal. I am afraid he has not realized that his proposal would only transmit single-phase current and is therefore useless. He also exhibited a table purporting to give annual losses, in which, by assuming that the dielectric losses in my system went on undiminished for the whole 24 hours, he obtained a figure of 8 000 000 units per annum. If Mr. Dunsheath will refer again to the paper, he will see that my proposed method of regulation involves the entire shutting down of 4 of the 6 cables at times of light load. The effect of this is that his figure of 8 000 000 units for the losses of my system becomes 3 200 000, or less than in his own scheme. If, again, his number of cables were increased to 8 (at 50 000 V) the dielectric losses (even at full load) *would be greater* than in my system. On the other hand, if he were transmitting 100 000 kW the losses (both copper and dielectric) would be greatly in favour of the six-phase/three-phase system, and still more so (in the case of the copper losses) if the load factor were better than 40 per cent. The reason why he is able to use 66 000 V is solely because he works his insulation up to 50 000 V per cm. With regard to Mr. Dunsheath's statement that the author implies that the carrying of load currents in the intersheaths is one of the advantages of the system but that this same advantage can be claimed for any intersheath system, I submit most positively that this is not the case. It is true that the plain tapping system for intersheaths is as effective as my own for all intersheaths nearer to the central core than a point which is at half-way potential, but for intersheaths outside this point—and this is just the part where they are most needed—the essential difference between the straight-tap method and my own is that the latter uniformly preserves its load-carrying value with undiminished voltage of transmission, whereas the other method rapidly falls off in efficiency. There is therefore no inducement to use more than one intersheath. This is the reason why, in the intersheath arrangement which Mr. Dunsheath's firm has patented, only one intersheath can be efficiently employed. It requires only a very small calculation to see that the more intersheaths we could employ the more effective would the scheme be; also, I would particularly point out that in my own scheme the final intersheath can be brought very close to the outside lead envelope, and that this intersheath performs a very valuable function, in acting as a pilot wire, to cut out the cable temporarily before the damage has penetrated into the same, and may be used as an emergency connection to prevent a complete shut-down where the cable is not burnt through sufficiently to disqualify it totally. Under these conditions the said arrangement is equivalent to no less than 6 spare cables, on the assumption that the trouble always enters the cable from the outside. The outermost lead sheath has also another very important function in that it eases the situation at the junction boxes, and the nearer it is to earth potential the less risk there is of a breakdown at the junction box due to water getting into the latter. No doubt there is some truth in Mr. Dunsheath's statement that intersheaths may be valuable in redistributing the heat—particularly in triple-core cables—but I must totally disagree with his statement that "if an intersheath cable were left without the ends connected to transformer tappings the results would be quite as good as if they were connected." On the other hand, I can quite believe that, Mr. Dunsheath being limited —from the point of view of efficiency—to the employment of only one intersheath, and—from the point of view of space—to even less than one intersheath (owing to his determination to put three cores in a given cable), he rather naturally came to the conclusion that intersheaths were useless. With regard to Mr. Dunsheath's "S.L." type of cable (see Fig. C) and the table of losses which he gives in connection therewith, I may say that after this table has been corrected in the manner I have already indicated the only conclusion I can draw from it is that the loss in the lead sheath with this type of cable is, as I should expect, considerably more than in an ordinary type of cable.

The remarks of Professor Fleming in reference to compressed air are most interesting, but I cannot say anything upon this subject, not having made any study of the same.

## North-Eastern Centre, at Newcastle, 11 December, 1922.

**Mr. H. W. Clothier:** The paper has two general objects with which we should all be in perfect sympathy: (1) The covering with metal of long transmission cables in preference to the use of overhead lines; and (2) the reduction in the initial costs of insulating these conductors by suitable grading of dielectric stresses (potential gradient). In these general principles switchgear manufacturers have met with some success, and their influence has extended to the transformer terminals and the generator terminals. In fact, metal covering is now a possibility for all connections between the generator and the load, with the notable exception of the long-distance transmission line in cross-country journeys where, in some cases, the increased cost of ordinary cables makes it too expensive as compared with overhead bare lines. These general principles have many advantages, e.g. safety to life, absence of interference by weather, elimination of the vexed problem of protection against lightning, and simplicity of maintenance. In fact, I was informed by an eminent engineer engaged upon transmission schemes across long distances in India, that, on account of the cost of patrol and repair, it was cheaper in the end to use high-tension cables than overhead lines. We have also the instance of the G.P.O., who are now engaged upon putting under ground a great many of their long-distance telephone lines. I think that the author should give us the cost of the overhead lines at 30 000 volts and 100 000 volts, to enable a comparison to be made with the cable schemes. I understand that by his method of connection there is some reasonable prospect of laying cables at a cost which would be little or no more than that of ordinary overhead lines. That being so, all that remains is to prove the economy and efficiency in operating the system. When one comes to examine it in detail, at first sight it seems so complex as to be likely to fail to receive that amount of welcome which its objects deserve. I have had the switches under Scheme B set out in diagrammatic form, and I had some difficulty in placing all the switches and transformers on the schedule. Under the major star transformers two sets of eight are given. I presume one set is an alternative to the other, but I can only find room for three at each end, so I presume that one at each end is spare. Comparing the systems, there must either be a considerable amount of energy lost in System B, or else it is designed for a more liberal load. System A has, at each end, 15 × 4 200 kVA = 63 000 kVA, whereas System B has (3 × 7 000 kVA) + (9 × 5 000 kVA) + (3 × 2 500 kVA), or a total of 73 500 kVA. Some adjustment of the connections would probably be necessary when the requirements for automatic protection against faults on the cables are investigated. Some scheduled as "isolating switches" would need to be automatic circuit breakers. Possibly the principles of self-balance protection could be applied to a pair of cables and the hexagon transformers but much complication would arise if we were to attempt to cut out one of a pair. I suggest also that the switching operations would require very careful handling. To close up on a line there would appear to be about 18 distinct switching operations to perform.

**Mr. R. J. H. Beaty**: The author has put forward a very ingenious scheme but there is one point with which I am not in agreement. The top of the hexagon is connected to the end of one phase of the "major transformer," presumably through a balance coil although it does not appear to be mentioned in the paper. The voltages supplied to the various cores of the cable are consequent voltages, the bottom of the hexagon giving a resultant, not a real earth. A dead short-circuit on one of the hexagon transformers might cause a potential difference of 60 000 volts between the outer conductor of the cable and earth. I see no reason why each hexagon should not consist of one three-phase transformer. The information given as to the behaviour of the dielectric is extremely interesting, and I feel that it could usefully be amplified.

**Mr. G. V. Twiss**: As one interested in overhead transmission, nothing would please me more than to find available, underground cables suitable for work at as high voltages as are possible with an overhead transmission line. Such high-voltage cables would be very helpful adjuncts to overhead transmission, not only for the bringing of transmissions into towns, but particularly in this country where one has to negotiate so many obstacles, such as road crossings, trunk P.O. lines, important railways and the like. The arguments in the paper are, however, in the main based upon the use of 33 000-volt cable to transmit 50 000 kW a distance of 30 miles. For such cases, however, this voltage is not an economic one, as the conductor requires a pressure certainly not less than 100 000 volts. To transmit this pressure a distance of 30 miles by means of overhead transmission, allowing, as an additional safeguard, two independent transmission lines, each carrying a single circuit, would cost not more than £150 000. Thus, based upon the author's data, we get the following comparison:—

| | £ |
|---|---|
| Using 33 000-volt underground cable .. | 1 000 000 |
| Using the author's system of underground cable at 100 000 volts .. .. .. | 500 000 |
| Using overhead transmission at 100 000 volts | 150 000 |

Thus, whilst the author claims a big saving on ordinary underground cables, yet it would only be justified where the overhead system could not be used. It is difficult, however, to conceive a case of a 30-mile line that is not in the main over open country, for which an overhead line is more suitable than underground cable, so that the case given by the author does not appear to be one of economic practicability. I therefore considered the application of the author's system to what seems to me to be the practical case, namely, that of leading-in off an overhead transmission line into a town by underground cable. Apparently, however, the proposed system would involve transformation, necessitating an expenditure at least equal to that of ordinary stepping-down, or, alternatively, the overhead line would have to be built on the author's system, the added cost of which would offset any saving due to avoiding stepping-down. I am unable, therefore, to see the application of the proposed system to practical cases of transmission of the nature which he himself cites. Nevertheless, he has clearly put a great amount of work and trouble into working out this system, and has drawn particular attention to what is achievable from the application of the study of dielectrics and gradients, and there is much in the paper and the new ideas behind it which will open up new avenues of thought and will doubtless be very helpful to the electrical industry.

**Mr. A. M. Taylor** (*in reply*): Replying to Mr. Clothier, I regret that at the moment I have not any definite figures of the cost of overhead lines, but I may say that some time ago I examined the detailed costs of a very important American overhead line, and my recollection is that these were approximately £0·1 per kW per mile. There was, I believe, a double line of towers, as well as circuits, and the cost of wayleaves for the towers was included. In the scheme proposed in my paper the cost of the cables, alone, approximates to £0·26 per kW per mile. At a very trifling extra cost, however, 100 000 kW could be transmitted over this line, and the cost in this case would be only of the order of £0·14 per kW per mile; and if it were possible to work at 150 000 volts and transmit 150 000 kW (as now seems more possible than when the paper was read) the cost would be reduced to about £0·1 per mile.

I greatly regret that I cannot fully answer Mr. Clothier's question about the transformers without extending this reply unduly. I may state here that his remark is substantially correct as regards the "B" system, except that it has (6 × 7 000 kVA) + (9 × 5 000 kVA) + (3 × 2 500 kVA), or a total of 94 500 kVA. The reason for this very large kVA rating is that the transformers are required to work at rather a low leading power factor, on account of the large condenser current, but, as pointed out in the estimate, if it should be found practicable to control the power factor in the way indicated in the paper, the requisite capacity of the transformers would be greatly reduced. The switching operations will, of course, be considerably simplified by adopting the arrangement of transformers which I have put forward in my reply to the London discussion (page 247). Possibly this diagram may sufficiently meet his difficulties.

In reply to Mr. Beaty, the top of the hexagon shown in Fig. 11 is connected to the end of one phase of the "major star" transformer through a balance coil, in the way that he presumes. This, however, is not the arrangement that I would naturally choose, but it appeared sufficient for the purposes of explanation. As a matter of fact, I had with me in London and Newcastle a lantern slide giving the arrangements which I should prefer, but there was no time to exhibit it. I do not consider that there is any serious point in Mr. Beaty's statement that "a dead short-circuit on one of the hexagon transformers might cause a potential difference of 60 000 volts between the outer conductor of the cable and earth." It is quite easy to prevent this. In any case the result would only be momentary and the cable should not be damaged by it. I do not consider that anything more need be provided for in my scheme than an insulation between any outer core and earth equal to withstanding 30 000 to 40 000 volts, if necessary, during emergency conditions.

In reply to Mr. Twiss, my proposal was not really intended to be employed for running across country, but has so far been designed exclusively for employment on railways. It remains to be ascertained whether the cost of running overhead lines across country will not be expensive if a duplicate line of towers be installed, and I maintain that nothing less than this should be done. Wayleaves have to be obtained, not only for the sites for the towers but also for continued access to these towers with repairing gear; and when the big towns are approached, or even in the more densely populated parts of the country between small towns, as in Lancashire, Yorkshire, Kent and Surrey, etc., it may prove very difficult to get wayleaves without considerable expense. Then there is a difficulty which I have already mentioned elsewhere, viz. the question of aviators flying into the overhead line in fogs or at night time, with possibly very disastrous results. Also, the question of malicious interference has to be considered. I have already mentioned in my reply to Mr. Clothier that the cost of my system if applied to transmit 150 000 kW at 150 000 volts would come down to the order of £0·1 per kW per mile. This would give interest and sinking fund charges, on a 30-mile line, of the order of 0·022d. per unit (total for whole line). I believe that a combination of the overhead system with my system for the entry into towns might not be impracticable, when we bear in mind that at least six of the conductors have to be insulated for only 15 000 volts to earth and another six for only 30 000/40 000 volts to earth. I agree with Mr. Twiss that my system should only be used where it is inadvisable or inexpedient to install the overhead system. If, however, wayleaves can be obtained along the railways and if the system become common both to the railways and to municipalities along the line, a very different aspect will be put upon the case.

## SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 13 DECEMBER, 1922.

**Mr. G. Rogers:** The advantages claimed for the new method of long-distance three-phase power transmission put forward by the author are of such an order that the scheme calls for the most careful attention of engineers interested in the matter. If the saving in capital cost of the new scheme as compared with the normal three-phase transmission at 30 000 volts by means of three-core cables is only half that claimed by the author, then it seems to me that a strong case has been made out. To turn to the practical consideration of the scheme the connecting up of the transformers and switchgear both at the sending and receiving ends would appear to be rather complex and difficult. I should like to ask the author how he proposes to dispose of the inner lead sheath at the terminal ends of his cable. Also, the question of the electric protection of the cable has not been mentioned, and perhaps the author will say whether he has considered this important matter. It would appear that the usual methods of protection would not apply, and special arrangements would have to be devised.

**Mr. F. Forrest:** The estimates of possible saving to be effected by the adoption of the author's system as against the use of ordinary three-core, 30 000-volt cables are so great that one wonders whether the estimates are based upon really reliable manufacturing costs. As far as I am aware there is no cable of the type proposed by the author as yet actually made, and, until the system has been tried, many people will regard these estimates of cost with a good deal of scepticism. The superiority of 25 periods over 50 periods for long-distance transmission has not been dealt with by the author and it would be interesting if, in his reply, he could indicate what the reduction in the losses would amount to if the lower frequency were used. When very high potentials and long-distance transmission lines are considered, especially when underground cables are used, the superiority of a low frequency becomes very marked, and from the point of view of dielectric and sheath losses it should be possible to produce a cheaper and more reliable cable with 25-period working than with 50-period working.

**Mr. R. H. Rawll:** I should like to draw attention to the formula $i_d = 2\pi fce/\sin\theta_d$, which appears on page 222. The author gives $e$ as the "voltage between core and intersheath." As a concentric ring of insulation is being considered, of which the capacity $c$ per foot length has already been calculated in a previous formula, and since $i_d$ is the capacity current flowing radially through this ring, $e$ must be the potential difference across this ring and not as stated above. An example will make this clear. If the tenth layer of insulation is taken, for the sake of argument, the voltage absorbed by this layer is (from Table 1, Appendix C) 1 840, which is obviously the value of $e$ to be used in the formula in question. If, however, $e$ is as defined above, this value would be 41 250 volts, i.e. the voltage between the core and this layer—a very different thing indeed. That the author does not mean this latter figure to be taken is very obvious from a perusal of the calculations given, and I merely point out this apparent discrepancy in case others, on substituting the various quantities into the equation, should find a difference between their own calculated results and those tabulated.

**Mr. W. J. Line:** In the right-hand portion of Fig. 8 the author proposes to superimpose on the two six-phase systems which are linked together, and represented by the two hexagons, a 123 000-volt single-phase supply. In Fig. 10 *et seq.* it is similarly proposed to superimpose a three-phase supply at increased voltage (represented by the "major star" in the figure) on the three interlinked six-phase systems represented by the three hexagons, and thereby transmit increased power. How does this affect the current-carrying capacity of the cables in the separate hexagons? It appears to me that the proposal must involve more current in the lines. Does not this mean that their size must be increased? On page 230 the author points out that at light loads the charging current in the line, due to its capacity, would be reduced to about one-third of its maximum. He proposes also to offset the charging or leading current by the magnetizing or lagging current of an induction motor or transformer load, and thus reduce or eliminate the wattless current to be supplied by the station. Now at times of light load, unless the reduction took place through the actual shutting-down of motors, the lagging or magnetizing current of the motor load would not fall off in the same way as the leading or charging current of the line. An induction motor takes the same magnetizing current whether running light or fully loaded. Therefore it appears to me that the lagging and leading currents could not always be balanced against one another under varying load conditions, and at times resonance conditions might arise. However, the proposal has the advantage that under all the circumstances the generating station would be relieved of the supply of some at least, if not all, of the wattless current.

**Mr. W. Lawson:** The author's scheme, owing to the exhaustive treatment of the details, appears at first to be unusually complicated, but this impression largely disappears with a fuller grasp of the scheme as a whole. In separating the phases, and in the particular method of employing intersheaths for the better distribution of dielectric stresses in the insulation, the author has succeeded in designing his cables without introducing any condition of working which is not already met with in E.H.T. transmission cables. The really novel and debatable feature of the scheme is the author's arrangement of the transformers. Here some complication creeps in with the necessity of having to employ a large number of transformers of various primary and secondary voltages, but providing there is no serious disadvantage in this (and such is not self-evident) the objection to the scheme on the score of complexity is discounted. Since the discussion the author has informed me that he proposes to discard the superposing transformers, while still transmitting power at 100 000 volts through the central cores. With this modification the scheme will take the form of a triple six-phase transformer scheme. The author mentions the difficulty of jointing single-core cables having a hempen centre. Does he consider this to be more serious than the jointing of his own cables? A valuable feature of the scheme consists in the possibility of taking up loads of poor power factor, with a gain in efficiency and regulation. I consider, however, that the figure of 0·7 which the author has assumed as the probable average power factor of the substations' loads is too low, in view of the attention which is now being given to the improvement of consumers' power factors. In the comparative costs of 30 000-volt and 100 000-volt schemes detailed in Appendix E, the costs of trunk cables for the former include laying, and excavating and reinstating streets, but apparently the cost of this work has not been included in the amount given for cables in respect of the 100 000-volt scheme. I shall be glad if the author will explain this point.

**Mr. A. M. Taylor** (*in reply*): Mr. Rogers raises the question of the electric protection of the cable. This has had some consideration, and I have discussed the matter with Mr. H. W. Clothier, and also indicated in the discussion before the North-Eastern Centre (page 250) a method of protection which I believe would be quite efficacious without the use of pilot wires. The problem is not nearly so complicated as it appears at first sight, but one must first get a thoroughly clear idea as to what the different currents are doing in the two systems.

In reply to Mr. Forrest, the estimates for the cables were given to me by thoroughly reliable firms, and since—in most cases—the same firms gave me estimates for ordinary three-core cables, they would not be likely to magnify the expense of the latter in their estimates.

In reply to his question as regards the superiority of 25 periods over 50 periods, it may be said that the doubling of the frequency doubles the hysteresis loss in the dielectric, and also doubles the capacity current; it quadruples the dielectric loss due to capacity current; it quadruples the regulation of the line due to the "capacity rise"; and it also quadruples the lead-sheath loss. It is therefore evident that a 25-period cable is inherently much less likely to break down than a 50-period cable, and, if this were the only question to be considered, one would say at once that it is most unfortunate for long-distance transmission by underground cables that 50 periods has been decided upon as the standard periodicity. It is therefore evident that considerably greater distances can be covered with 25 periods than with 50 periods, also that armoured cables can be safely used, with negligible loss in lead sheath and armouring.

Mr. Line is correct in surmising that additional copper is required for the superposed current. It is stated in the paper that additional copper to deal with this current is placed in the central core at a quite reasonable extra cost on the cable. Mr. Line's statement that an induction-motor load takes the same magnetizing current, whether running light or fully loaded, is correct. What he has not pointed out, however, is that as the load on the induction motor is reduced, the reduced load becomes the equivalent of a greatly increased dead resistance, and this dead resistance is of itself quite sufficient to check any resonance. There is also the other point of view, i.e. that motors are switched completely off and on, and, as they are all in parallel with one another, the magnetizing component of the motors left in circuit is equivalent to a large reduction in the total magnetizing component of all the motors on the system; from both points of view, therefore, the movement is in the right direction.

I thoroughly concur with Mr. Lawson's remarks, and I am pleased to note that he agrees that the scheme becomes a simple one when the superposed major star is removed. On the question of power factor I should like to ask Mr. Lawson to bear in mind that Birmingham is particularly favoured in the matter of power factor owing to its large rotary-converter and tramway load, but that even in Birmingham the pure motor-load power factor is sufficiently low to fulfil my suggested conditions. In reply to his last remark, I do not debit my scheme with the cost of excavation and of remaking the streets, because it presupposes the running of the cables along the main lines of railway by the permission of, and for the benefit of, the railway companies.

# ELECTRIC ARC WELDING APPARATUS AND EQUIPMENT.

By J. Caldwell, Member.

(*Paper first received* 24*th July, and in final form* 17*th October*, 1922; *read before* The Institution 14*th December*, 1922.)

### Summary.

The intention of this paper is to deal with the physical features of the iron arc as used for welding ferrous metals, so far as those features are known, indicating some of the lacunæ in present knowledge; and to describe the general types of apparatus and equipment which have been developed, illustrated by some examples of each type, and some of recent design which promise well.

The two branches of the subject are directly connected, because the apparatus must conform in its performance to the conditions of the welding arc and to the requirements of the welder.

Operating or workshop methods are touched on only so far as they illustrate or determine, or are determined by, the physics of the welding arc and the practical requirements of welding.

Working methods and applications of arc welding have been described in several recent contributions to other Institutions and Associations, in technical journals, and in books, reports, etc. A short list of the more important of these within the author's knowledge is set out in Appendix II at the end of the paper.

### Contents.

(1) The state of the art.
(2) Iron-arc characteristics.
(3) Direct-current versus alternating-current welding.
(4) Electrodes.
(5) Current density.
(6) Polarity.
(7) Direct-current single welders.
(8) Direct-current multiple-welder sets.
(9) Welding circuit regulation.
(10) Alternating-current welder sets.
(11) Copper, brass and bronze welding.

*Appendixes.*
I. Classification of flux-covered electrodes.
II. Recent publications.
III. Experimental results.

## (1) The State of the Art.

Arc-welding practice is in advance of theory. It is an established fact that good welds can be made on any ferrous material if certain conditions are observed, and the standardization of these conditions has been established for many applications by empirical methods. As usually happens in an empirical art, there is considerable divergence of opinion on many points which can only be reconciled by the establishment of exact knowledge.

Arc welding was originally tried for repair work, either because there was no other method or because it was evidently quicker and cheaper than any other. It was looked on with suspicion, but when time was of importance and new parts were not readily obtained, the successful use was worth risking and failure did not harm the existing position. During the war the conditions favouring such trials were intensified, and the generally good results obtained greatly widened the applications, developed welding as a regular repair process and led to its adoption for constructional work.

Ship repairers led the way in this empirical development, assisted by their wide knowledge of ferrous materials and methods of joining them up into structures exposed to severe, complex stresses. They have had the co-operation of electrical engineers, metallurgists and chemists, who have investigated the subject, each from his own point of view. There has been a certain amount of systematic research work, directed, however, rather more to immediate practical results than to fundamentals.

A greater knowledge of the physical foundations of the process is desirable as a guide for practical development, and as a basis for confidence. If it can be demonstrated that this method of uniting steel and iron parts gives consistently good results, not inferior to the older methods, the saving in weight and labour will lead to its adoption as standard practice in lieu of the older methods of riveting, screwing and bolting.

A great deal of work has been done to ascertain the electrical conditions necessary for good work, their more or less automatic control by suitable apparatus, the adaptation of electrode material and fluxes to the particular metals to be welded, and the training of operators.

The object of this paper is to endeavour to put the results of this work on record, within the limits indicated above. The paper does not deal with carbon-arc welding, which is well established for certain manufacturing work, except to mention some physical facts which have a bearing on the iron-welding arc.

## (2) Iron-arc Characteristics.

The physics of the carbon arc as applied to lighting have been investigated by Mrs. Ayrton in her well-known work. Making allowance for the difference in the behaviour of the electrode materials and the purposes to which it is applied, it is assumed that the facts established are generally true for metallic arcs, and the iron arc in particular.

The distinctive characteristic of an arc is that the current is carried by a gaseous or quasi-gaseous conductor composed of gas, vapour, very fine solid particles, or a mixture of such bodies, across a gap between terminals or electrodes which by volatilization or disintegration furnish a supply of the quasi-gaseous conductor. It is therefore essential that one or both of the electrodes shall be maintained at a temperature producing such volatilization or disintegration. The gaseous conductor behaves as one having a negative temperature coefficient: high temperature is a condition of its conductivity. The volatilization temperature is produced by the passage of the current across a relatively high surface resistance or contact resistance located at the junction of the gaseous conductor and the electrode. The electrode in the carbon arc is solid, while in the iron (and other metallic) arc it is liquid, i.e. molten. This contact resistance appears to be related to the volatilization temperature and heat of the electrode material, and to require a minimum current density for any particular electrode material. This results in a fixed voltage-drop at the contact surface where volatilization occurs. The voltage-drop along the gaseous conductor is proportional to its length, so that it appears to have a definite specific resistance. If volatilization takes place at one electrode only, as in the direct-current carbon arc, the surface resistance and voltage-drop are lower at the other electrode. In the carbon arc the temperature at the volatilization surface is higher than at the other, i.e. the positive electrode is hotter than the negative. The volatilization surface is the seat of the highest temperature in the arc.

The total voltage-drop between the electrodes is therefore the sum of three terms: two at the contact surfaces between the electrodes and the gaseous conductor, and one in that conductor. The surface voltage-drops are fixed for any particular electrode material, while that of the gaseous conductor is proportional to its length. For variations in current, the electrode material and arc length being fixed, the contact-surface areas and the cross-section of the gaseous conductor automatically vary so as to keep the current density in each constant. The resistance of the whole arc therefore varies inversely with the current passing, and the arc is unstable in itself. These statements are subject to qualifications, but are at least first approximations. The conditions of the carbon arc change suddenly at a current density which brings the positive contact surface (crater) to the edge of the electrode, producing the unstable "hissing" arc.

The numerical values of the voltage-drops and some other elements have been investigated by Mrs. Ayrton for the carbon arc in air. For arcs between metallic electrodes they are not definitely known. There is evidence that, between iron electrodes of equal size, the positive electrode gas-surface develops more heat than the negative. Presumably, therefore, it is similar to the carbon arc in having a higher voltage-drop at the positive electrode. It is known that the total voltage-drop across an iron arc is considerably less than that across a carbon arc, and it is probable that this lower voltage corresponds to a smaller amount of energy consumed in the volatilization of iron compared with that required to volatilize carbon. The energy of volatilization is not a question of temperature only, different metals, as they have different "latent heats of fusion," doubtless having different "latent heats of volatilization." In the special case of carbon, volatilization takes place from the solid state, the liquid state being non-existent at ordinary pressures, so that the latent heat of a double change of state is involved. From calorimeter determinations on fuels, the heat of vaporization of carbon from the solid amorphous state is 3·231 calories per gramme, or 5 817 B.Th.U. per pound. The temperature of volatilization is about 3 600° C. The author is not aware of similar data for iron or other metals of high melting point.

In the carbon arc the volatilization temperature is reached at the positive electrode only, with a drop of about 30 volts. According to Mrs. Ayrton, the volatilized carbon is projected from the positive to the negative electrode as a "carbon mist." In air some of this carbon mist is burnt, with the production of a sheath of flame around the arc proper. Some of it—in arcs of normal length—reaches the negative electrode, on which it is deposited.

It has been rather generally assumed that a similar projection of metal takes place across an iron arc, from positive to negative, but this is not in accordance with welding practice. Deposition takes place equally well whether the electrode or the work is positive, and at least as well with alternating current as with direct current. It may be suggested that the cause of the transfer of iron is different from that in the case of carbon, but there is at present no ground for supposing that there are different processes to bring about similar results. Both cases are covered by the single statement that electrode material is transferred from the hotter to the cooler electrode. The question as to whether the transferred metal travels in the state of vapour, a fine spray, or otherwise, has been much discussed, and there are various opinions. One American investigator claims to have proved that it is in the form of drops numbering 30 000 to the ounce, which may be called a spray. That there is a definite projection is certain, for in overhead and vertical welding the iron passes against gravity from the electrode to the work. Although there is evidence that more heat is evolved at the positive electrode than at the negative, the greater mass and conductivity of the work keep the temperature below that of the electrode, even with the work positive.

The minimum pressure needed to maintain an iron arc is known to be about 15 volts. This covers the sum of the two surface resistances and that of the gaseous column. The separate values of the three terms are not known. As the welding arc is very short, it can be said that the sum of the two surface voltage-drops is something under 15 volts. This is not very different from one-third of the similar drop in a carbon arc. In a carbon-iron welding arc with a ½ inch diameter carbon negative, an arc length of ¼ inch and a current of 200 amperes flowing, the total arc voltage is 22. If the voltage-drop at the carbon is the same as at the negative of a carbon-carbon arc, i.e. about 9 volts, these figures indicate that the principal difference between the carbon and iron arcs is in respect to the voltage-drop at the positive electrode. Probably the conditions of a welding arc are analogous to those of a "hissing" carbon arc, in which the voltage-drop at the positive is less than in a steady arc.

From these statements it appears that there are two very definite openings for research on the welding arc, viz. (1) In what state does the iron cross the arc, and what conditions determine its transit ? and (2) What is the distribution of voltage-drop in the iron arc ? Another is : What are the quantitative relations of this transfer of metal to the electrical and other variables ?

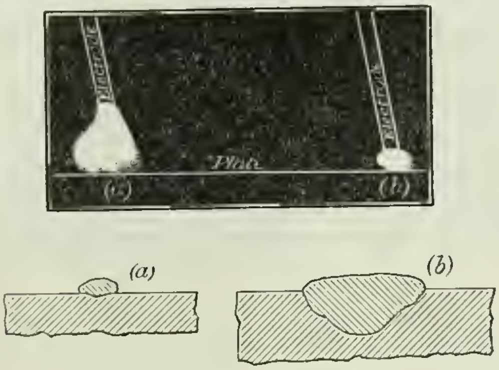


Fig. 1.—Long and short arcs.

The practical object of research on the subject must be to determine the conditions which make the useful transfer of electrode material a maximum. " Useful transfer " covers a rather wide ground.

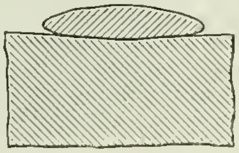


Fig. 2.—Small penetration.

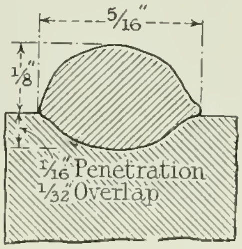


Fig. 3.—Good penetration.

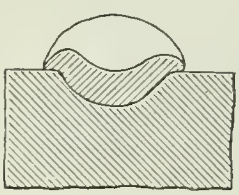


Fig. 4.—Good penetration of crater.

Like the carbon arc, the iron arc behaves as if it had a negative resistance, i.e. an increase of current across an arc of fixed length reduces the voltage-drop. It is therefore inherently unstable, and, since good welding demands the maintenance of a steady current proportioned to the size and composition of the electrode and the character of the work, all welding equipments have to include some means of adjusting the current and keeping it within limits during the operation.

The figure of 15 volts for minimum welding-arc voltage-drop is derived from tests made with direct current, bare iron electrodes and automatic feed of the electrode. With hand operation the voltage is always higher, i.e. from 22 to 25 volts. This is for the mechanical reason that the hand cannot maintain steadily the very short arc, about $\frac{1}{16}$ inch, corresponding to the minimum voltage, but has to work with a minimum length of about $\frac{1}{8}$ inch. Flux-covered electrodes appear to permit of a somewhat greater working length and voltage, thus rendering the manipulation easier. It is rather difficult to measure the true arc length with flux-covered electrodes, as the metal " cups " a little above the edge of the covering.

If the arc is lengthened much beyond the figures given, good welding is impossible. The iron passing across the arc burns to oxide, absorbs nitrogen, and the deposit is contaminated, permeated with blow-holes, mechanically weak, and may fail to unite with the metal of the work. The arc length at which this defect commences is variously stated as that corresponding to from 27 to 30 volts. It is probably rather higher for covered electrodes and for alternating current.

The fact that good welding can be done only within a rather narrow range of arc length and voltage imposes another condition on welding equipments, i.e. they should not permit of an arc voltage exceeding the maximum for the deposit of good metal. If an arc is drawn beyond this it should be extinguished. Fig. 1 shows the appearance of long and short arcs, and their effect, and Figs. 2 to 6 illustrate degrees of penetration.

This condition has to be reconciled with the fact that the open-circuit voltage must be in considerable excess of the arc voltage to provide for the voltage-drop in the steadying resistance or reactance required to make the circuit reasonably stable, and also to permit the arc to be struck readily.

Facility of striking the arc is an important element in the time and labour costs of arc welding. Whilst a sufficient open-circuit voltage is necessary, if the circuit conditions permit the passage of a very large current at the moment of contact the electrode may stick or " freeze " to the work, making a sort of resistance weld, which is not wanted. As the longest electrode which can be conveniently used is consumed in a run of 1 to 3 minutes, such interruptions add materially

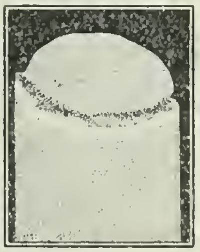


Fig. 5.—Good penetration (section).

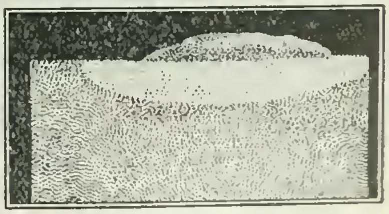


Fig. 6.—Poor penetration (section).

to the time spent in changing the electrodes. Fig. 7 shows photo-micrographs of welds.

Some experiments designed to throw light on certain of the questions raised in this section of the paper have been made by Mr. H. M. Sayers and Mr. Langdon Davies at Faraday House and elsewhere. These experiments and the deductions from them are described in Appendix III.

### (3) Direct-current versus Alternating-current Welding.

Good welding can be done with both direct and alternating current. There are preferences, and as direct current had the start more operators and others were in favour of direct current than of alternating current. The best electrical conditions are slightly different, and there are differences in the actual manipulation, but experience shows that operators who have been accustomed to one readily adapt themselves to the other. It is also the case that flux-covered electrodes are essential for alternating current, apparently because the lagging effect of the flux and slag maintains the necessary temperature during the periodical current reversals. The only real difference is that the striking of the arc is rather more difficult with alternating current.

A higher open-circuit voltage is required with alternating current. With direct current an arc can be maintained with a minimum of 45 volts (open circuit), but 60 volts is much easier to work with and can be taken as the practical figure. A higher voltage permits of an excessive arc length and a poor quality of deposit.

With alternating current the open-circuit voltage should be from 75 to 90 volts. The difference between the arc voltage and the open-circuit voltage has, in the case of direct current, to be taken up in a steadying resistance, while a reactance is used with alternating current. There is therefore not so much difference in the steadying losses as might be supposed. It may, indeed, be possible to make alternating current more efficient in this respect than direct current, as will appear later in the descriptions of some of the equipments available. The alternating-current arc has a lagging power factor, but the magnitude of this depends a good deal upon the steadying and regulating equipment, and it need not be lower than that of the average works induction motor at full load.

Where it is desired to make use of a general public supply for welding, direct current imposes the necessity for the use of some form of motor-generator. The pressure of the public supply mains is generally 200 volts or more. To take from such mains welding currents of from 30 to 200 amperes per operator is not practicable or economical, for, in addition to the waste, the large bulk and high cost of the resistances, the open-circuit voltage is far too high. Further, public supplies generally have an earthed neutral, and the earthing of the work welded, which is often unavoidable and always advisable, cannot be permitted by the supply authorities, who also will not be pleased by the intermittent peak of hundreds of amperes. With an alternating-current supply the voltage reduction requires only a transformer.

### (4) Electrodes.

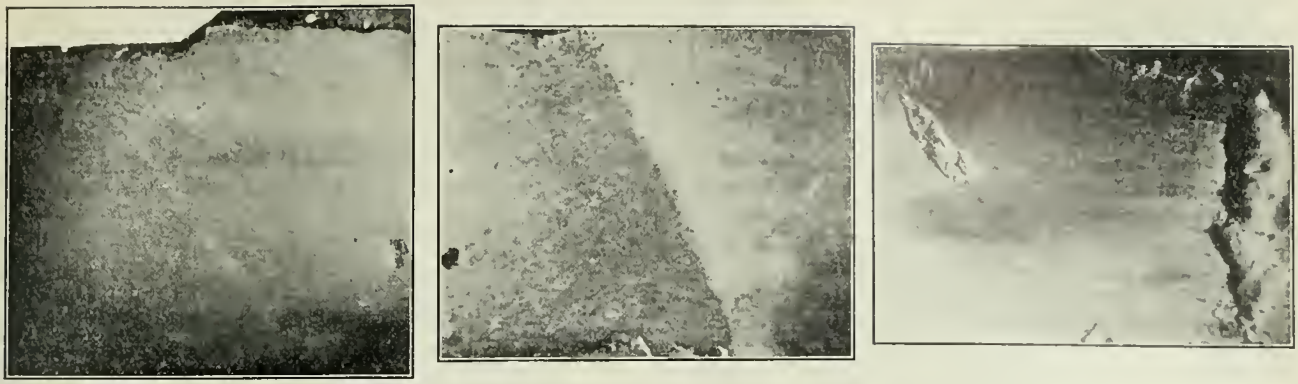
The first iron-arc welding was done with bare-wire electrodes. These are still widely used, and for some kinds of work where strength is not material the welds made may be satisfactory. With direct current operating on mild steel and wrought iron, flux-covered electrodes provide better results. For welding cast iron, high-carbon steels and alloy steels, and generally with alternating-current welding, flux-covered electrodes are necessary.

With bare electrodes there is oxidation of the electrode itself beyond the arc, and of the weld metal and work whilst they are hot. A suitable flux-covering protects the electrode beyond the arc, forms a protective slag on the deposited metal and work, and reduces the access of air to the arc itself. The arc length is somewhat greater and the current steadier, probably because the current is confined to the electrode end, and it cannot reach the outside. Manipulation is easier, as the arc can be struck on hot slag without any liability of the electrode to "freeze on." The deposit from a covered electrode on to a flat surface spreads more than that from a bare electrode, owing to the fluxing action of the slag, thus making a wider union and a neater finish.

Coated electrodes are essential for use with alternating current, probably because the coating and slag conserve the temperature during the periodic variations of the current.

The flux coating plays a very important part in welding high-carbon steels and alloy steels and cast iron, where it is necessary to obtain weld metal approximating in composition and structure to those materials. The electrode metal passing through the arc is considerably altered in composition ; for example, carbon and manganese are burnt, or rather oxidized, by the reducing influence of the arc. The flux coating reduces the amount of this change, and may impart or restore the desired constituents. Whether this action takes place in the arc, or between the flux and the deposited metal, or partly in each, cannot be said. In the manufacture of steel the reactions between the metal and the flux in the furnace are essential parts of the process, and the composition of the flux is carefully adapted to the product desired. In arc welding, however, the time available for reaction is very short. This short time, the high temperature and the fine division of the electrode metal passing through the arc, are conditions widely different from those of the steel furnace, and a great deal of experiment has consequently been needed to arrive at the proper fluxes for different materials. In matching any particular steel the composition of the electrode and the flux co-operate. The electrode metal does not, as a rule, match that of the material. The work of producing electrode and flux combinations which will make good welds in different materials has met with great success. It has necessarily been done empirically, as no general principles can yet be formulated.

In the result, cast iron, manganese steel, nickel steel, stainless steel and other special alloy steels are all successfully arc-welded by the use of appropriate electrodes and fluxes.



A

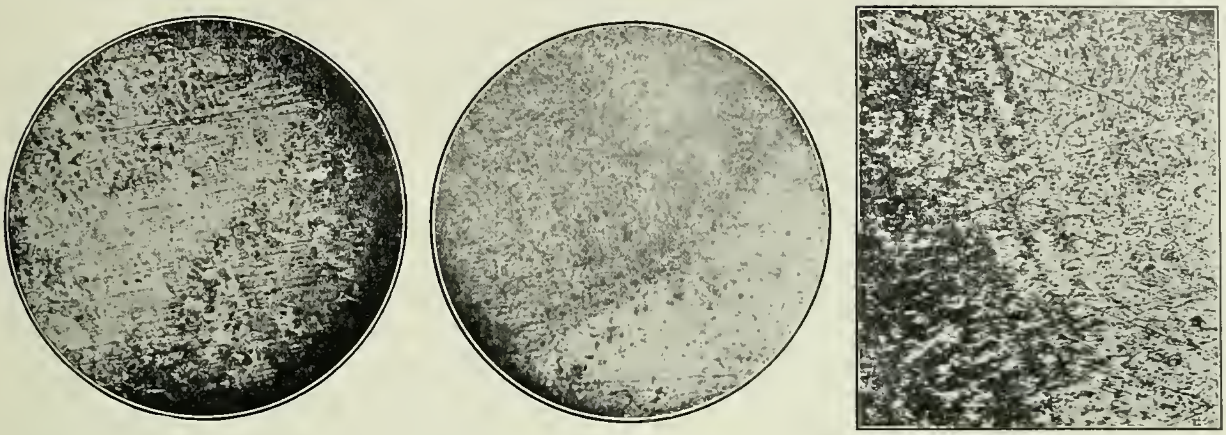
Magnification = 8 diameters.

B

Magnification = 8 diameters.

C

Magnification = 8 diameters.



D

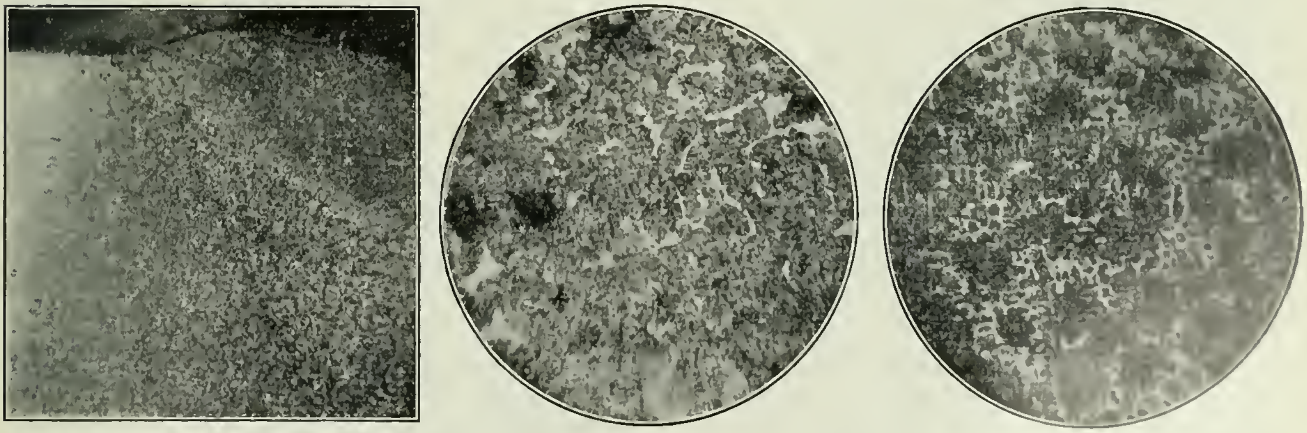
Magnification = 40 diameters.

E

Magnification = 40 diameters.

F

Magnification = 120 diameters.



G

Magnification = 4·8 diameters.

H

Magnification = 120 diameters.

I

Magnification = 120 diameters.

FIG. 7.—Micrographs of arc welds: A to F are of mild steel; G, H, I are of cast iron.

(A) and (B), good welds. (C), poor weld; gas trapped on weld line and in weld metal. (D) and (E), weld or interfusion line. (F), weld line. (G), cast iron weld. (H), weld line of (G). (I), weld metal of (G).

For most purposes a flux coating of a basic nature is desirable, but in some cases it is of an acid description. An aluminium wire or tape is sometimes included, and nickel plating is also used. Both these metallic additions tend, in different ways, to reduce oxidation of the electrode metal, and may also have other effects.

The metallurgical and chemical actions of the coating and the flux formed by it have to be reconciled with other requirements. The coating must fuse at a slightly higher temperature than the metal, while the slag formed must be very liquid and light so that it will rise to the surface before the metal solidifies and will spread over the hot weld and so protect it from the air. The flux should dissolve or reduce the iron and other oxides. The glassy skin of cooled slag should be easily removed from the welded surface by brushing or light hammer chipping, and the coating must be sufficiently tough and adherent to the electrode to withstand transport and handling. In working, the coating must fuse evenly without flaking and must keep level with the end of the electrode. There is usually a little "cupping," i.e. the electrode end is a trifle inside the fused rim of coating. Deep cupping is, however, objectionable, as a projecting rim of fused coating interferes with the arc striking and misleads the operator in respect to the length of arc. Whilst hot the slag is a semi-conductor and the arc may be struck on it without any risk of the electrode sticking.

Intermediate between bare and coated electrodes are dipped electrodes, i.e. electrodes dipped into a "slurry" of a basic nature. This coating has some protective influence on the electrode as against oxidation, and reduces spluttering and current fluctuations as compared with bare electrodes. It is not a substitute for flux coating.

### (5) CURRENT DENSITY.

The current required for welding depends mainly upon the thickness and mass of the parts to be joined. It may be said roughly that the dimensions of the work determine the current, and the current determines the size of the electrode. For each gauge of electrode there is some maximum manageable current. If this maximum is exceeded the electrode fuses far beyond the arc, large portions drop, the current fluctuations are wild and the arc is turbulent and unmanageable. For coated electrodes the maximum currents range from 60 amperes for No. 14 gauge to 200 amperes for No. 4 gauge. The current densities thus vary from about 12 000 amperes per square inch for the smaller, down to about 5 000 amperes per square inch for the larger. Somewhat higher current densities can be used with bare electrodes. The American practice, which is chiefly with bare electrodes, is to use 10 000 to 12 000 amperes per square inch.

An electrode is capable of welding properly with two-thirds or less of the maximum current, so that six gauges, i.e. Nos. 4, 6, 8, 10, 12 and 14, cover a long range of work. A current of 200 amperes and a No. 4 electrode are about the manageable maxima for hand welding. Whether automatic welding will permit of larger values has not yet been determined. Automatic arc welding is hardly beyond the experimental stage in commercial service.

The statement made above (that the current is determined by the dimensions of the work) is subject to some qualifications. For example, in making a butt weld between two plates, say, $\frac{3}{4}$ inch thick, the edges will be bevelled, forming a V of an angle of about 60° when approximated. The first run of welding must be done with a small electrode, say No. 8, in order to get the electrode to the bottom of the V, which must be first filled. A second run is then made over the first with a larger electrode, and a third may be necessary. As the area or width increases, the electrode size and current required increase.

Mr. H. M. Hobart, who has taken a leading part in electric arc-welding development and research in the United States, says that the largest current which can be used makes the soundest welds. Too large a current for the thickness and mass of the work burns holes in it.

Welding thin sheet is practicable but has not been much developed, possibly because oxy-acetylene and resistance welding have a firm hold on this class of work. Recent experiments, however, promise good results, and thin sheet arc welding may prove commercially valuable.

### (6) POLARITY.

It is the established practice to make the work positive and the electrode negative. This practice seems to have originated with carbon-arc welding, the reason being that, with a positive carbon electrode, carbon is carried across the arc into the work, and the weld is unmanageably hard. With iron electrodes the reason for making the work positive is that, as more heat is evolved at the positive electrode, the greater conductivity of the work is countered and the work surface raised to the fusing point with a smaller current than would otherwise be necessary. The total heating of the work, and expansion and other troubles due to such heating are reduced. It is exactly analogous to the well-known fact that to solder fine work with the smallest heat-damage, the soldering bit should be as hot as possible.

### (7) DIRECT-CURRENT SINGLE WELDERS.

*Output.*—For general-purpose sets, the maximum loading is 200 amperes at 60 volts. This current is about as large as can be managed in hand operation.

*Regulation.*—This is the special problem of the single-welder set. The ideal characteristic for such a machine is a flat voltage characteristic from zero up to the full current for which it is adjusted, and a very rapid voltage-drop with any greater current. A general-purpose machine must have some means for varying the current at which this voltage-drop occurs. To prevent sticking, it is necessary to limit the current on striking the arc. It is desirable that current fluctuations caused by the unavoidable variations in arc length shall be checked and limited. The requirements may be summarized as follows :—

(1) A drooping characteristic for any current beyond that fixed by adjustment.

(2) A uniform voltage for currents up to the set or adjusted load, with little or no increase at no load.

(3) Very rapid regulation to counter the effect of arc variations.

The devices employed with more or less success to meet these requirements can be roughly classified as follows :—

(1) Excitation methods. Combinations of self excitation, separate excitation, direct and reversed series excitation. Special arrangements of the magnetic circuit, including pole disposition, proportions and shapes of poles, pole-pieces and yokes, calculated to vary the armature reaction with different load conditions. External regulators acting on the exciting circuits.

(2) Regulation of speed or torque of driving engine or motor by electrical control of governor or transmission clutch.

(3) External regulators controlling resistances in the welding circuit, sometimes acting simultaneously on one or more of the exciting circuits.

With those automatic regulations it is always necessary to adjust the field rheostats to suit the current needed for the particular work in hand. The ideal set requires only this one adjustment, the automatic devices keeping the output at that level.

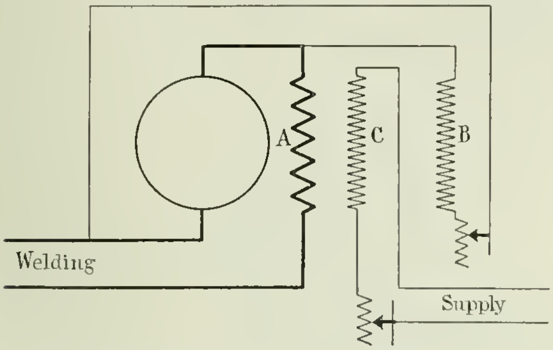


Fig. 8.—Connections of Premier welding set.

Most of the single-welder sets on the market employ one or more of the devices classified above, and some of them are very complex. Such devices as separate exciters and multiple field windings cause a generating set to be larger and much more expensive than a plain generator of the same maximum output.

A sufficient rapidity of regulation to counter arc irregularities is rather difficult to secure. Magnetic flux-changes in fairly massive iron circuits involve time-lag, and inductive action between different windings on the same magnetic circuit has to be allowed for. It is doubtful if the generator can be so altered as to control arc fluctuations. An American designer has recently found it necessary to explain his proposals for a thoroughly automatic single welder by several pages of equations culminating in determinants which reduce into cubic equations and have a forbidding appearance.

Single-welder sets are generally arranged for mounting as self-contained portable machines, with internal combustion engines of the motor-car type, or with driving motor, on trucks or otherwise to suit the users.

The examples selected for illustration are in use, and are typical of the many different machines proposed to give characteristics meeting the requirements of arc welding by automatic variation of excitation.

(i) *Kramer type*, adopted for the Premier set. The connections are shown in Fig. 8.

A = reversed series winding in welding circuit.
B = shunt winding, self-excited.
C = shunt winding, separately excited.

B and C are wound in the same sense, and A in the opposite sense. In series with B and C there are rheostats for the regulation of the welding current.

(ii) *Macfarlane type*, adopted for A.W.P. set. The connections are as in Fig. 9.

Four-pole field.

A = shunt winding on one pair of diametrically opposite poles, separately excited.
B = shunt winding on other pair of diametrically opposite poles, self-excited.

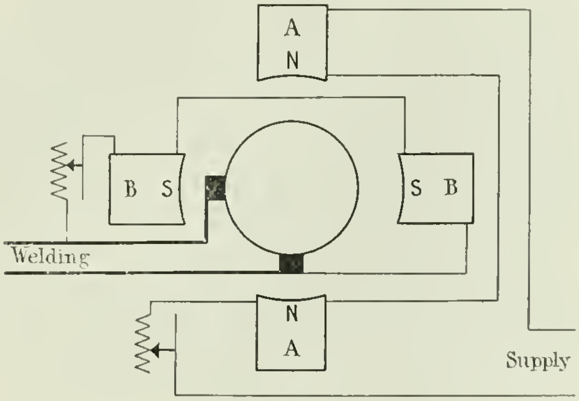


Fig 9.—Connections of Macfarlane (A.W.P.) welder.

A and B are wound in the same sense, and each has a rheostat in series for the regulation of welding current.

The pole-piece form, etc., are designed to facilitate armature reaction, giving a result similar to that of a reversed series winding.

The characteristics of this machine with the regulator in three different positions are shown in Fig. 10.

(iii) *Westinghouse, American.* The connections are as in Fig. 11.

A = shunt field, separately excited.
B = reversed series winding.
C = commutating winding.
D = shunt winding, differential. This winding is self-exciting while the generator voltage exceeds the separate supply voltage, as reduced by the rheostats ; and is reversed and assists the series winding to limit the generator voltage when striking the arc.

A characteristic of this machine is shown in Fig. 12.

(iv) *Split-pole type* (*General Electric Co., American*). The connections are as shown in Fig. 13.

A = shunt winding, self-excited, on main poles, viz. those on the horizontal diameter.
B = shunt winding, self-excited, on cross poles, viz. those on the vertical diameter.
C = series winding in welding circuit, on cross poles, reversed with respect to the shunt winding.

The main poles are normally saturated ; the cross poles are not saturated but provide a path for the armature reaction flux, which is assisted by the series winding. The series turns are adjustable for different welding currents. At a given load the cross field is reversed by the sum of the armature reaction and the series winding effects. On short-circuit the reverse field cancels the main field, giving zero voltage. At any load the voltage is proportional to the arithmetical sum of the main and cross fields.

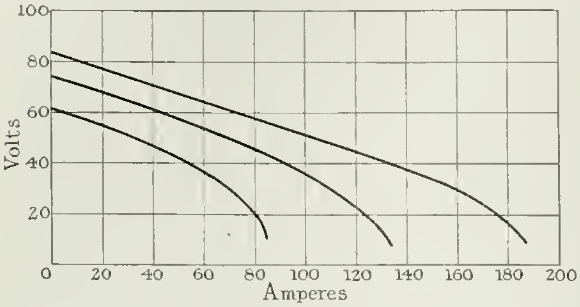


FIG. 10.—Characteristics of Macfarlane (A.W.P.) welder.

(v) *Simple shunt-series combination* (*Mawdsley and others*). The connections are shown in Fig. 14.

A = shunt winding, separately excited.
B = series winding in welding circuit, reversed.

Some of the machines of this type have pole-pieces, etc., designed to facilitate armature reaction.

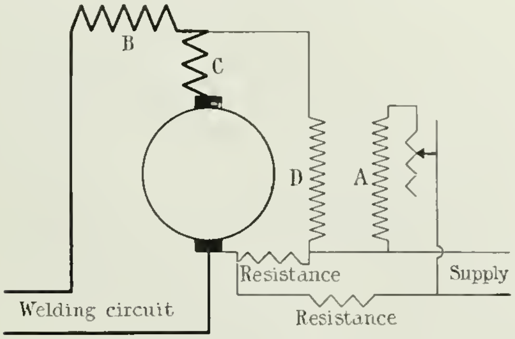


FIG. 11.—Connections of Westinghouse (American) welder.

With the two field windings so disposed to have considerable mutual induction, there is a large rise of current during a few hundredths of a second on a short-circuit, as shown in Fig. 15.

*General.*—When used as self-contained sets, driven by engines, belt, or a.c. motors, the machines shown as having separate excitation require an exciter in addition to the main generator. When driven by d.c. motors the separate excitation can be given by the supply circuit.

Commutating poles are generally necessary.

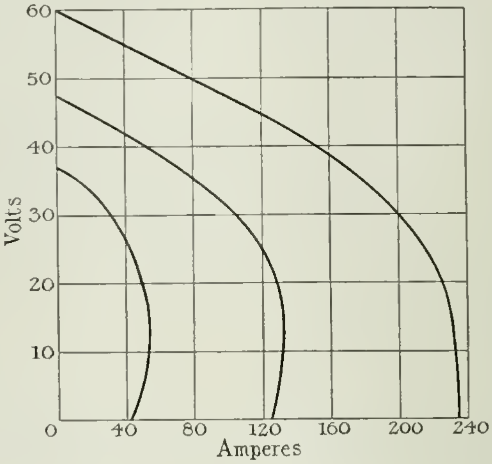


FIG. 12.—Characteristics of Westinghouse (American) welder.

Entirely laminated magnetic circuits improve the regulating action. The adjustments to suit different welding currents are made on one or more of the exciting windings.

An exhaustive paper on " The Design of Constant-Current Generators for Arc Welding," by Mr. K. L. Hansen, appeared in the *Transactions of the American Institute of Electrical Engineers*, 1920, vol. 39, part 2, p. 1357.

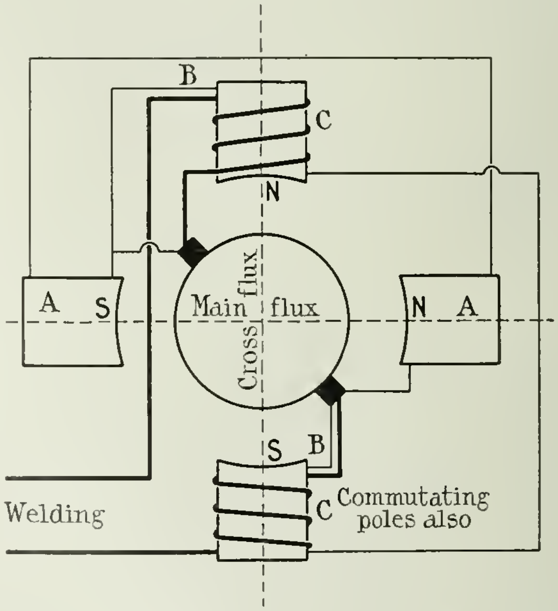


FIG. 13.—Connections of General Electric (American) welder.

Balancer welding machines, dividing the supply current into motor and welding current, with various arrangements to produce the welding characteristic, have been used, but the general objections to welding direct from a public supply are not removed by their use. They are less wasteful than the stabilizing resistance needed to take up the difference between the welding and the supply voltages.

*External field regulation.*—Designs of automatic regulators using the welding current to act on the generator fields have been proposed, but do not appear to be in use. The American Westinghouse Company supplies a "flat compounded" machine with a panel adjustment of the series and commutating windings, which appears to regulate by armature reaction effect.

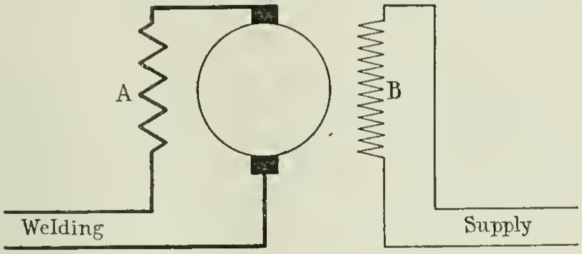


FIG. 14.—Connections of reversed series, separately excited welder.

*Regulation by drive.*—The only example known to the author is the Davies-Soames set. The connections are as shown in Fig. 16.

A magnetic clutch is interposed between the driving motor and the generator. There are three windings on the clutch magnet: A, separately excited; B, in series with the welding circuit; and C, shunt-excited by the generator.

Winding A predominates normally. Windings B and C both oppose A. When the welding current in winding B overpowers that in A the clutch slips. The welding current is adjusted by rheostats in circuits A and C. Winding C also weakens the clutch magnet to slipping point if the generator voltage becomes excessive.

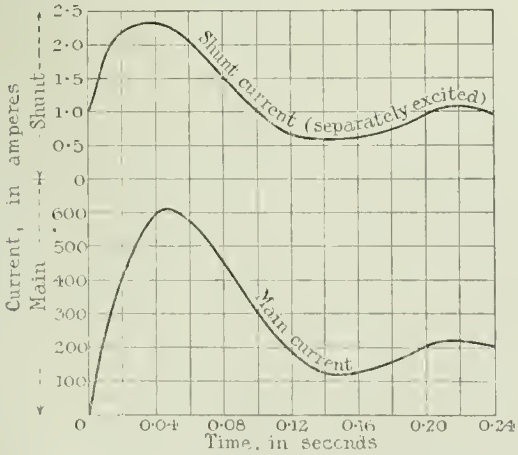
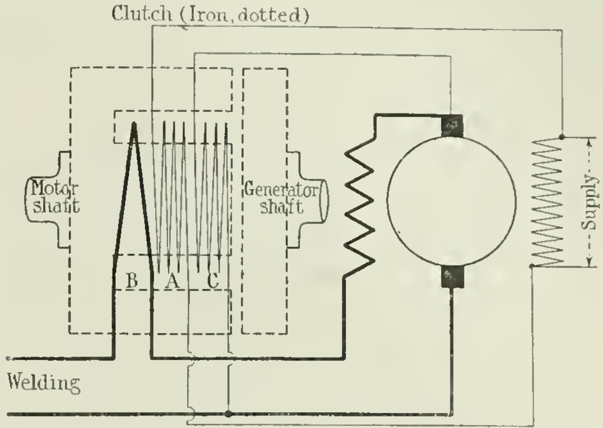


FIG. 15.—Short-circuit characteristic of reversed series, separately excited welder.

The generator is compound-wound. The shunt winding is separately excited from the supply circuit, and the series winding is cumulative, not reversed. If driven by an engine or an a.c. motor an exciter is necessary.

A characteristic curve is shown in Fig. 17. In this figure E represents the welding current for which the set is adjusted.



*NOTE:-Rheostats in circuits A and C are not shown*

FIG. 16.—Connections of Davies-Soames magnetic clutch welder.

(8) DIRECT-CURRENT MULTIPLE-WELDER SETS.

Generators to supply a number of welders should give constant voltage at all loads from zero to the simultaneous maximum demand of all the welders. As the fluctuation of load is extremely violent the self regulation must be very prompt. Compounding should cover the voltage-drop in the mains as well as the variation of speed with load in the driving motor. Separate excitation and a quick-acting automatic regulator in the shunt circuit are advisable, and commutating poles are essential. It will lessen the risk of mutual interference by the welders if a rather higher voltage than 60 is provided.

Multiple welders in general are "flat compounded" machines, with commutating poles. The regulation for each welder is effected by separate resistances. The welding circuits are all in parallel.

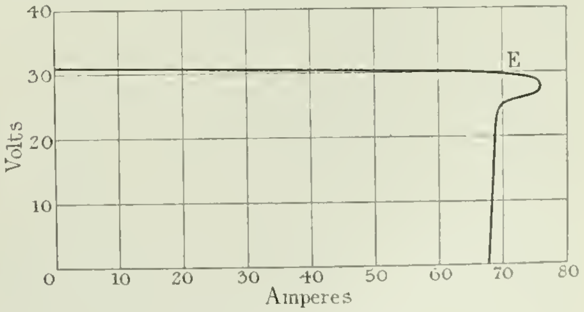


FIG. 17.—Characteristic (at 70 amperes) of Davies-Soames magnetic clutch welder.

The Wilson equipment has a carbon-pile resistance with a solenoid in the welding circuit acting against a spring which compresses the pile. The adjustment is made by shunts on the solenoid. This machine is made as a single or multiple welder.

One American company makes a constant-current series multiple welder, in which the individual welder adjustments are made by shunts on the main line. When welding is not in progress the shunt is short-circuited. The machine regulates for constant current, and variable voltage, much as a series arc-lighting machine. The machine seems only suitable for factory use on bench work where the work can be insulated and is of a fairly uniform character.

*Performance and testing.*—A satisfactory characteristic obtained by the usual method of varying the circuit resistance does not prove that a machine will be satisfactory for welding. In welding, the transient effects of load variations are important and are not shown by the usual tests. The rapid fluctuation of a welding load is a severe test of commutating qualities. The only satisfactory test of a welding set is to make good welds with it, using the different current values which will be required in actual work.

*Stabilizing rheostats.*—There is a somewhat general opinion among welders that the stabilizing resistance in direct-current welding are improved by the addition of a certain proportion of reactance. Evidently reactance is calculated to reduce the rate of current fluctuation, and particularly to reduce " sticking " on striking the arc. Such reactances must be adjustable for different welding currents, and obviously must include air-gaps. It seems more logical to provide the reactance in the generator itself, particularly in the form of armature self-induction. Flux-covered electrodes give smaller fluctuations than bare electrodes and at least reduce the need for external reactance.

### (9) Welding-circuit Regulation.

Each welder requires a resistance which he can adjust to pass the current required by the work in hand. It is generally stated that this resistance should include some reactance, as the amplitude of current oscillations is thereby reduced. Evidently the reactance should also be adjustable to suit the working current. Reactance probably assists in striking the arc, as it chokes down the current-rush on making contact, and adds a little to the circuit voltage as the contact is broken. Such reactances must have air-gaps, which may be adjustable to suit various currents. One device used to assist the arc striking is an automatic switch which cuts out some resistance as soon as the arc starts.

These resistances have to dissipate from 1 to 6 kW each as long as welding is being done. They are therefore more bulky and expensive for their capacity than starting resistances and the like which are only in use intermittently, and a much more liberal design is necessary. They have to be located within reach of the welders. It is therefore worth while to pay attention to their design in respect to working temperature, ventilation, bulk and protection. The grid form is robust and convenient if made with steel units, otherwise coils are to be preferred. A tapered resistance, i.e. one in which the cross-section is reduced at the successive taps, saves material as compared with a uniform section of resistor. Usually the welding lead terminates in a plug inserted into sockets connected to the taps. Some resistance material could be saved by arranging for sections to be connected in parallel and series combinations, but this would require some form of controller, with doubtful net saving. A finer adjustment than that provided by the taps is sometimes used, and this is advantageous for the finer classes of work. Squeeze-up carbon piles are not suitable for the main resistances, as their resistance changes too much with temperature, and they do not give sufficient range. They are, however, fairly satisfactory for fine adjustment. Evidently, where welding equipments are intended for uniform work, a lesser range of current adjustment is needed than where the work is of a varied character.

### (10) Alternating-current Sets.

It may be assumed that alternating current will always be taken from a public or works general supply and transformed to the welding voltage. Whilst the current fluctuations on the supply side will be reduced in the transforming ratio, they may still be considerable in the view of the supply undertaking. Welding is a single-phase load with a lagging power factor, and the supply engineer will naturally want to be consulted as to the arrangements. If the supply is three-phase the welding current disturbs the balance of the phases. This can be met to some extent where a number of welders are in use, by dividing them between the phases, or single-phase current can be taken from a three-phase transformer by the well-known method of connecting the secondaries in series with one winding reversed. This equalizes the currents in the primary phases, but in two of them the currents are 60° out of phase, one leading, and the other lagging. It is for the supply undertaking to decide which is the less objectionable, and the user should agree with them at the outset.

Alternating-current welding requires 75 to 90 volts on open circuit. The difference between this and the arc voltage is taken up by means of a reactance in the circuit.

The equipment for a.c. welding is therefore a transformer, to give 75 to 90 volts at the secondary terminals on open circuit and to carry the maximum welding current required for the work to be done. An adjustable reactance takes the place of the resistance used with direct currents.

The capacity of single-welder sets for a full range of welding is 12 kVA. For multiple-welder sets the transformer capacity may be less, say from 6 to 8 kVA per welder served.

Whether anything is to be gained by using a multiple-welder transformer as against a separate transformer to each welder depends mainly upon the distribution of the welders in the particular case considered. If all the welders are in one shop so that the secondary leads are short, the saving in transformer cost may be worth while. If they are widely distributed over a large factory or shipyard the cost of the long secondary leads may easily outweigh the saving on the transformers. Single-welder transformers may advantageously be designed with an internal reactance which reduces the amount of external reactance that has otherwise to be provided. There may also be a saving in the cost of current effected by the reduction of the total iron losses if single-welder transformers are used. Each case has to be considered on its own conditions.

The open-circuit voltage required for a.c. welding may, in some working conditions, be dangerous. The Home Office has for this reason objected to a.c. welding in some exposed positions. To prevent this danger, apparatus has been devised which reduces the open-circuit voltage to 25 volts and also facilitates the striking of the arc.

A fixed reactance does not produce the drooping characteristic desirable for arc welding in the sharp way necessary ; the choke should increase very rapidly if the desired current is exceeded. Several forms of a.c. single-welder apparatus are described below :—

(*a*) *Ordinary transformer.*—For a complete range of work the output of a single-welder transformer is 200 amperes at 60 volts, with an open-circuit pressure of from 75 to 90 volts, depending somewhat on the class of work to be done. This implies considerable internal reactance. It is convenient to have tappings at 5-volt steps to allow for conductor resistance and for variation in the electrodes and stock metal. An adjustable reactance with sockets to take the electrode plug is required for current adjustment. With this simple equipment good work can be done and the set can be used in any part of a factory, shipyard, etc., where the a.c. supply is accessible.

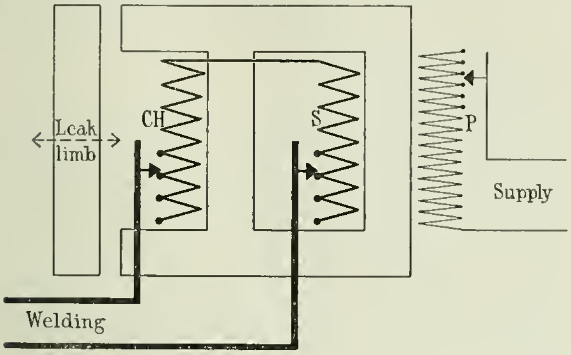


Fig. 18.—Connections of Holslag welding transformer.

(*b*) *Holslag welding transformer* (*The A.C. Cutting and Welding Company*).—This transformer has a third winding in addition to the primary and secondary windings, which is put on a separate iron limb connected to the main yokes, and an unwound limb stands between the common yokes with an adjustable air-gap (see Fig. 18). It is a combined transformer and choke coil, but with mutual inductance and a common leakage path between the two elements. Provided with tappings on primary, secondary and choker windings, and the adjustable leakage path, many combinations may be made. The inventor claims for it a wide range of welding utility. The mutual inductance between the choker and the transformer windings is stated to stabilize the circuit more effectively than an independent choker. Sets are made up for one-, two- and three-phase supply. A description of the device and its theory will be found in the *Transactions of the American Institute of Electrical Engineers*, 1920, vol. 39, part 2, p. 1435.

(*c*) *Davies-Soames automatic regulator* (*Daysohms, Ltd.*).—This apparatus resembles a wound rotor induction motor. The stator and rotor windings are in series, and are of equal numbers of turns. The rotor is free to rotate within limits against certain restraints. In the no-load position the windings produce nearly co-axial opposed poles and magnetomotive forces in the iron, with a minimum reactance. When current is passing the rotor tends to rotate in the direction increasing the resultant flux and reactance, up to the position where the poles are co-axial and the magnetomotive forces are added. This is the position of maximum reactance. With 2-pole windings the angular movement from minimum to maximum choke is obviously 180°. The rotation is opposed by a spring, the force of which can be regulated and damped by a dash-pot. The minimum choke can be regulated by an adjustable stop which limits the rotor movement in the direction given by the spring.

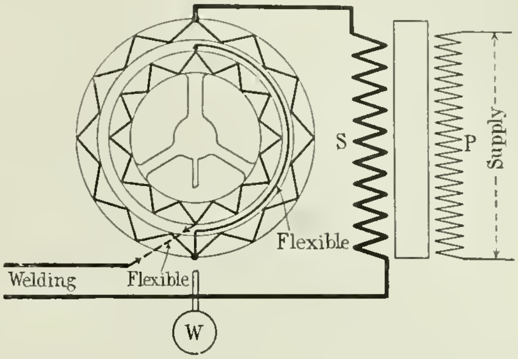


Fig. 19.—Connections of Davies-Soames automatic regulator.

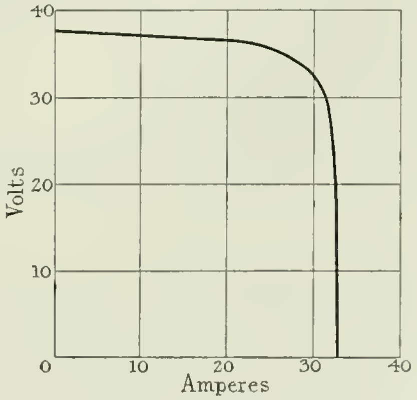


Fig. 20.—Characteristic (at 25 amperes) of Davies-Soames automatic regulator.

To adjust the regulator for welding, the spring is regulated for the desired welding current, and the stop is fixed for the choke corresponding to the arc-striking current. The open-circuit voltage is that of the transformer but on striking the arc the circuit voltage drops instantly, due to the operation of the choke, and the rotor moves until the current torque is balanced by that of the spring. In practice it is found that this regulator gives a very nearly constant current, viz.

that at which the rotor and the spring torque just balance, with a very sharp voltage-drop if that current is exceeded. This drop is not dependent upon the movement of the rotor. As the voltage can only increase sensibly with a decrease in the current, a long arc cannot be maintained, being extinguished by the current-drop. Fig. 19 gives a diagram of the arrangement, a weight being shown instead of the spring actually used; and Fig. 20 shows a characteristic curve of the performance.

The latest form of this alternating-current arc welder embodies the same principle, by which the striking and the welding current are separately adjustable, and consists of a transformer and choke coil in one unit, the choke coil being, as before, provided with a dashpot and adjustable stops to limit the movement of its keeper, and a spring to return it towards zero, which will give the full range of 25 to 200 amperes in infinite gradation. This unit is arranged for direct connection to any alternating-current mains, and as it weighs only about 3 cwts. and is fitted with castors, it is very easily moved about a works.

(*d*) *Alternating-current welding safety device* (*Daysohms, Ltd.*).—Fig. 21 is a diagram of this apparatus, with the connections. In addition to the main or welding transformer there is an auxiliary transformer the secondary of which gives 25 volts, and the work is connected to one end of each of the two secondaries. The electrode lead passes through a solenoid, the core of which pulls on a switch lever. With no current passing and the core down, the switch connects the electrode to the other terminal of the 25-volt secondary, so that the open-circuit voltage between the electrode and the work or earth is 25. On touching the work with the electrode to start the arc, the core is pulled up and the switch moved, first to an intermediate contact connecting to the main transformer through a resistance, and then to a third contact which cuts out the resistance, the switch breaking from the 25-volt terminal just before the third contact is made. The additional resistance at the moment of striking reduces the current-rush and so prevents sticking. When the arc is broken the core drops back and the welding transformer is disconnected from the electrode. It is understood that the Home Office accepts this device as removing the shock danger from alternating-current welding.

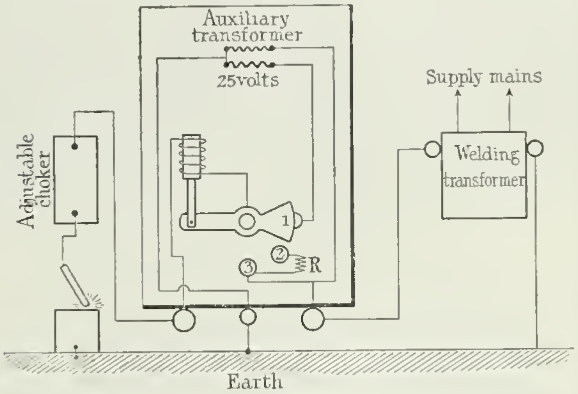


FIG. 21.—Connections of Davies-Soames safety device.

### (11) COPPER, BRASS AND BRONZE WELDING.

As the result of recent research work, three types of electrodes are now available for the purpose of welding and depositing non-ferrous metals.

The perfection of these products to a commercial stage represents the latest development in the successful application of electric arc welding for construction and repair.

The metal core is of tinned copper, surrounded by a flux covering, which adheres firmly to the welding rod and does not break away when subjected to transport and workshop usage. This flux covering is of special composition to suit the nature of the copper alloy to be welded, and produces a powerful reducing atmosphere around the work to ensure the deposition of good metal in the weld.

Copper and the various alloys of brass and bronze in general use have a very short temperature-range between the welding and fusion points, and practice is necessary to prevent the metal becoming fluid or remaining in a sluggish condition. Care must be taken to prevent the parts being welded from being pierced by excessive heating.

The heat conductivity of copper is very high, and the deposited metal will lose its heat to the work unless this is pre-heated to a sufficiently high temperature. Therefore, when using these non-ferrous electrodes it is advisable to pre-heat the work before starting the welding operation. In the majority of cases local heating along the line of the weld is sufficient, and this may be applied by a blow-lamp. Whenever possible the joint to be welded should rest upon come refractory material, e.g. carbon, asbestos millboard, or furnace lining material.

It is not necessary or advisable to hammer the metal deposited, as this is perfectly homogeneous and free from blow-holes.

The electric current requires to be regulated according to the nature and dimensions of the material to be welded. Once this has been ascertained, however, the welding operation should be proceeded with as rapidly as possible, when no difficulty will be experienced in welding copper, brass and bronze with entire satisfaction.

The author takes this opportunity of thanking the several firms supplying electric arc-welding plant and equipment for granting facilities to gain a knowledge of the apparatus described in the paper. He also wishes to record his appreciation of the freely offered assistance received from Mr. H. M. Sayers and Mr. Langdon Davies, and the co-operation of Messrs. H. M. and F. M. Sayers in contributing Appendix III which has revealed the mechanical actions and the functions of the flux covering of electrodes, in some respects leading up to the determinations of the physical features of the welding arc.

## APPENDIX I.

### Classification of Flux-covered Electrodes.

| *Type* | *Description* |
|---|---|
| (1) Standard | To give a weld strength of 26 tons per square inch. |
| (2) Special tensile A | To give a weld strength of 29 tons per square inch. |
| (3) Special tensile B | To give a weld strength of 35 tons per square inch. |
| (4) Cutting | For cutting with the electric arc. |
| (5) Overhead | For welding in an overhead position, specially suitable for boiler repairs. |
| (6) Carbon A | To deposit 1·5 per cent carbon steel. |
| (7) Carbon B | To deposit 1 per cent carbon steel. |
| (8) Carbon C | To deposit 0·75 per cent carbon steel. |
| (9) Carbon D | To deposit 0·5 per cent carbon steel. |
| (10) Carbon E | To deposit 0·25 per cent carbon steel. |
| (11) High-speed steel | For depositing high-speed steel on tools, drills and cutters, and for reinforcing. Deposit adjusted to suit type of work. |
| (12) Self-hardening | An electrode providing a hard steel deposit. |
| (13) Manganese steel | For depositing 14 per cent manganese steel. |
| (14) Nickel-carbon steel | For welding nickel-carbon and high-tensile steel. |
| (15) Electrode for depositing cast iron | Forms a high-quality cast iron which flows readily and is machinable, but should only be used when pre-heating is possible. |
| (16) Soft iron | For repairing heavy cast-iron structures which cannot be pre-heated; also for work requiring a high degree of ductility. |
| (17) Stainless steel | For welding all kinds of stainless steel and iron. Deposits stainless steel of highest quality. |
| (18) Copper | To weld and deposit copper. |
| (19) Brass | To weld and deposit the various alloys of brass required. |
| (20) Bronze | To weld and deposit the various alloys of bronze required. |

## APPENDIX II.

### Bibliography of Electric Welding.

T. T. Heaton: "Modern Methods of Welding," *Proceedings of the Institution of Mechanical Engineers*, 1914, pts. 1 and 2, p. 151.

C. B. Auel: "Electric Welding," *Transactions of the International Engineering Congress*, Paper No. 136.

J. F. Lincoln: "Electric Arc Welding," *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34.

H. S. Marquand: "Modern Methods of Electric Welding," *Journal I.E.E.*, 1915, vol. 53, p. 851.

"Electric Welding at L.B. & S.C. Railway Works," *Railway Gazette*, vol. 22.

J. H. Bryan: "Progress in Electric Welding (Cost Table)," *Boiler Maker* (*U.S.A.*), 1916, vol. 16; *Railway Mechanical Engineer* (*U.S.A.*), vol. 90.

"Notes on Electric Welding," *Electrical Review*, 1916, vol. 78, pp. 91, 132, 183 and 211.

P. A. E. Armstrong: "Manganese Steel Welding," *Electric Railway Journal* (*U.S.A.*), 1916, vol. 47, p. 1144.

Report on Electric Arc Welding, by the Committee of Railway Electrical Engineers, *Power* (*U.S.A.*), 1916, vol. 44.

P. A. E. Armstrong: "The Efficiency of Arc Welding," *Welding Engineer* (*U.S.A.*), vol. 2.

A. M. Candy: "Electric Arc Welding," *Transactions of the American Institute of Electrical Engineers*, 1917, vol. 36, p. 1159.

E. P. Jessop: "Repairing German Vandalism by Electric Welding," *Society of Naval Architects and Marine Engineers*, 1917, vol. 29.

E. Oberg: "Electric Arc Welding," *Machinery* (U.S.A.), 1917, vol. 24.

J. Caldwell: "Notes on Welding Systems," *Transactions of Engineers and Shipbuilders in Scotland*, 1917–18, vol. 61, p. 206.

J. Caldwell: "Reports on Electric Welding and its Application to Ship Construction," United States Shipping Board (Emergency Fleet Corporation).

J. Caldwell: Report on Applications of Welding to Ordnance Construction, United States War Dept., June 1918.

H. J. Cox: "Application of Electric Welding to Ship Construction," *Society of Naval Architects and Marine Engineers*, 1918, vol. 26.

H. A. Hornor: "Electric Arc Welding. A new Industry," *Transactions of the American Institute of Electrical Engineers*, 1918, vol. 37.

R. S. Kennedy: "Boiler and Other Repairs by Electric Welding," *Transactions of the Institute of Marine Engineers*, 1918, vol. 30, p. 45.

H. M. Sayers: "Notes on Regulations for Arc Welding," Paper read before the Institution of Electrical Engineers, 12 December, 1918.

W. F. Jacob: "Bibliography of Electric Welding," *General Electric Review* (*U.S.A.*), 1918, vol. 21, p. 652.

Articles on Electric Welding, *General Electric Review* (*U.S.A.*), 1918, vol. 21, pp. 836–968.

Researches on Electric Welding, Minutes of Research Sub-Committee of Emergency Fleet Corporation (U.S.A.).

T. T. Heaton: "Electric Welding," *Proceedings of the Institution of Mechanical Engineers*, 1919, Jan.–May, p. 49.

H. M. Hobart: "Welding Mild Steel," *Transactions of the American Institute of Mining Engineers*, 1919, vol. 37.

S. V. Goodall: "Welding in Ship Construction," *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, pt. 1, p. 113.

O. H. Escholz: "Fusion in Arc Welding," *ibid.*, p. 121.

J. H. Paterson: "Electric Welding (Research)," Association of Engineering and Shipbuilding Draughtsmen (Newcastle District). Publication of Technical Section, February, 1919.

"Electric Welding" (Appliances, Problems, etc.), *Engineer*, 1919, vol. 128, pp. 213, 442, 472 and 529; also *Engineering*, 1919, vol. 107, pp. 148, 153, 158, 254, 281, 350, 782 and 817.

J. Caldwell and H. B. Sayers: "Electric Welding Developments in Great Britain and U.S.A.," *Proceedings of the Institution of Civil Engineers*, 1919, vol. 208, p. 69.

W. S. Abell: "Application of Electric Welding to Large Structures," *ibid.*, p. 104.

J. Reney Smith: "Application of Electric Welding in Ship Construction and Repairs," *ibid.*, p. 127.

W. L. Lorkin: "Electric Welding and its Applications," *Journal of the Royal Society of Arts*, 1918–19, vol. 67, p. 304.

H. Haramiishi: "On the application of Electric Arc Welding to two Vessels," The Japanese Society of Shipbuilders, read November, 1919.

W. H. Gard: "Some Experiences with Electric Welding in Warships," *Transactions of the Institution of Naval Architects*, 1919, vol. 61, p. 260.

H. S. Marquand: "Electric Welding: its Theory, Practice, Applications and Economics," *Electrician*, 1919, vol. 82, pp. 331, 350, 377, 468, 495, 515, 541, 565, 591, 645, 681 and 705.

D. Lagrange: "Le Soudage Electrique," *Bulletin de La Société Belge des Électriciens*, 1920.

J. Caldwell, "Electric Welding in the Shipyard," *Times Engineering Supplement*, April, 1920.

L. Miller: "Electric Arc Welding," *B.E.A.M.A. Journal*, 1920, vol. 7, p. 306.

J. Caldwell: "Present State of Electric Arc Welding," *Journal of the Junior Institution of Engineers*, 1920, vol. 31, pt. 4, p. 145.

Articles on Electric Welding (Machine Designs and Characteristics), *Transactions of the American Institute of Electrical Engineers*, 1920, vol. 39, pp. 1411–1435.

H. Tondelier: "Le Soudage à l'Arc Electrique," *Société Belge des Ingénieurs et des Industriels*, 1920.

F. M. Farmer: "Standardization of Testing Welds," *Proceedings of the Institution of Mechanical Engineers*, 1921, vol. 1, p. 225.

J. Caldwell: "Modern Electric Welding Practice," *Electrical Times*, 1921, vol. 59, p. 451.

H. M. Sayers: "Electric Arc Welding," *Tramway and Light Railway Association Journal*, July, 1921.

J. Caldwell: "Welding Conditions in England," *American Welding Society*, 1921, vol. 13, pt. 2, p. 13.

"Arc Welding (Deposition of Alloy Steels)," *Daily Telegraph, Engineering Notes*, Dec. 12, 1921.

J. Caldwell: "Electric Arc Welding in Steel Structures," read before the Cardiff and Manchester Branches of the Institution of Mechanical Engineers, January, 1921; *Engineering*, 1921, vol. 111, p. 55.

A. T. Wall: "Electric Welding for Ship Construction," *Proceedings of the Institution of Mechanical Engineers*, 1922, vol. 1, p. 239.

Numerous papers in the publications of the American Welding Society, 1921–22.

## APPENDIX III.

### AN INVESTIGATION OF THE IRON WELDING ARC.

By H. M. Sayers, Member, and F. M. Sayers.

The object of the investigations described in this Appendix was to obtain some knowledge of the iron welding arc, with a special view to some indication of the conditions determining the transfer of metal from the electrode to the work, and the state of the metal during the transfer. The experiments have been confined to the alternating-current arc at a frequency of 50 periods per second, that being the available supply.

*Testing arrangements.*—Optical projection is the obvious way to examine an arc, both visually and photographically, and it permits of some magnification, which is essential with the very short arc that produces a satisfactory deposit.

To get the arc in a fixed position necessary for optical projection and photographing, an apparatus was made which resembles a lighting arc lamp. The electrode is clamped in a holder on a rack which is fed to the work by a series motor through a suitable train of gearing. A brake solenoid connected across the arc checks the feeding speed when the arc voltage is low, and vice versa, so that the arc length is kept approximately constant. There is also a hand-moved regulator in the driving motor circuit, so that the operator has an independent control of the feeding speed and, consequently, of the arc length. The "work" is represented by a strip of plate clamped to the periphery of a circular table, which is geared to the driving train and revolves at a speed proportional to the electrode feeding speed. The electrode is horizontal, while the "work" strip is vertical and part of a cylinder. A long camera is mounted to one side with some freedom for swinging about a vertical axis passing approximately through the arc, so that the best aspect of the arc can be chosen, and small variations in its position followed by the observer at the screen end. A shutter rotated by a synchronous motor is fitted between the arc and the camera lens, and the stator of the motor is rotatable about its own axis so that the phase at which the arc is imaged can be varied. For photographing purposes there is fitted to the screen end of the camera a plate holder adapted for use with either a stationary or a falling plate. The magnification obtained is about 4 diameters, and the falling-plate speed such as to give two complete periods (1/25 second) in about 3 inches, so that two periods are obtained on a quarter plate. The arrangement permits of spectroscopic observation of different parts of the image.

It will be seen that the position of the electrode and work is that of "vertical" welding. As only alternating current is available all the work has been done with covered electrodes, some types of which were found to work much better than others. The criterion for this work is that with the mechanical feed the arc shall be maintained steadily for the useful length of an electrode, i.e. about 16 inches. As this is consumed in rather less than a minute there is only just sufficient time to observe or photograph when there are no interruptions of the arc.

For recording the arc voltage and current curves a small oscillograph was made, with a falling-plate camera, which gives also two periods on a quarter plate.

*Supply conditions.*—The supply conditions were adjusted by some preliminary trials until the deposit proved good, and were subsequently kept constant. The frequency is 50 periods per second, the open-circuit voltage of the welding transformer about 68, the steadying impedance is partly a choking coil and partly a resistance, the electrodes are No. 14 S.W.G. closely wound with asbestos yarn coated with a flux compound, kindly supplied by Messrs. Alloy Welding Processes, Ltd., and the current is approximately 30 amperes.

*General appearances.*—Observing the magnified image on the screen with the shutter stationary, one sees that the surface of the work is hollowed and rippled, the ripples being roughly concentric and moving outwards towards the rim of the crater. The crater surface appears to be of clean, molten metal. Surrounding it there is a red-hot rim of matter in ebullition, presumably molten slag. At the end of the electrode the covering melts with a steady rotation at the rate of four or five revolutions per second. At each rotation one turn of the asbestos yarn is removed. The molten covering forms drops at the lower edge of the electrode, parts of which fly across to the work at frequent intervals. The path appears to be outside the vapour body.

The arc or vapour mass is of no very definite or constant form, and rapidly changes shape. At the electrode end it appears to be of rather larger diameter than the electrode, and apparently an overlap of it rotates and removes the covering, as described above. It narrows at the work end and seems to terminate on a very bright part of the crater on the work, a patch smaller than the electrode diameter, and of irregular and changing shape. Between the two the arc expands a good deal on the upper side, but not so much on the lower side. It gives the impression that, but for the effect of gravity, it would take a spherical shape, but with a somewhat large segment cut off by the electrode boundary. The colour of this arc is a blue-violet, and there is no appearance of any drops or particles traversing it. To the eye it is not brighter than the electrode and work surfaces, but the colour of the latter is bright red to orange, or nearly white, while that of the arc is blue, as stated. Photographed without any colour screen, the arc is far brighter than anything else excepting the bright patch where it seems to terminate on the work crater. It has not been possible to see the actual electrode end, as the flux covering masks it, suggesting that the metal surface is decidedly within the edge of the covering.

Photographed on a dropping plate (with the shutter open and stationary) the arc shows as two bright patches per period. The width of these patches corresponds to about two-thirds of an alternation; and they are brightest in the centre, shading off to a sharp edge. The image of the bright spot on the work crater is nearly continuous but is not so bright.

Observed visually with the synchronous shutter and a certain position of the stator, the appearance is not materially different from that obtaining with no shutter. On rotating the stator, i.e. altering the phase of the shutter opening, the blue vapour mass fades and finally, for a space centred on a 90° angle from the maximum arc size and brightness, the vapour mass disappears. The electrode end and the work crater surface are seen glowing, and the surrounding slag boiling, the inference being that the arc is extinguished, or the blue vapour mass non-existent, for a definite interval on either side of the zero-current points.

*Oscillograms.*—Oscillograms have been made, using the falling-plate method. The open-circuit voltage is approximately sinusoidal. The voltage curve with the arc established has much steeper sides and a broad two-peaked maximum. The arc-current curve is a triangular peak with a base of about two-thirds the duration of each alternation. The other third is at zero value. This duration corresponds to the falling-plate photograph of the arc, and appears to mean that the current passes only while the vapour body is in existence. Presumably the current is interrupted and the arc stops at some point in the descent of the voltage, and both are re-established on the following reverse rise of the voltage. It is clear that the arc duration in each alternation corresponds to that of the peak of the voltage curve, the valley between the two peaks of the voltage maximum to the rapid rise of the current, and the rise to the second peak to the rapid fall of the current.

At the time of preparing this Appendix no calibrated measurements have been made of these oscillograms, but it is hoped to make some in subsequent work.

*Spectroscopic appearances.*—Only visual observations have been made with a small direct-vision spectroscope. These show a bright-line spectrum of the arc body, which seems to be chiefly the arc spectrum of iron, though the sodium D line is strong, doubtless from the flux composition. Satisfactory observations of the electrode and work spectra during the periods of arc extinction have not yet been achieved. It is hoped to improve the apparatus sufficiently to succeed in these, and perhaps to obtain spectrographs photographically.

*Temperature distribution.*—With an image of the arc in a nearly stationary position on a screen it seems possible to investigate the temperature distribution by a thermopile or other means of measuring radiation. This has not, however, yet been attempted.

*Method of transfer of metal.*—The observations made do not justify any decisive statement as to the way in which the iron is transferred from the electrode to the work. They seem, however, to indicate that the arc body is chiefly iron vapour at a temperature considerably above the melting point of the metal. It is possible that this vapour body sheathes and masks a stream of very fine droplets of molten iron, but so far nothing of the kind has been observed. The molten flux-covering does visibly pass from the electrode to the work in fairly large drops, but, as above stated, outside the arc, and below it in this case of vertical welding. The current oscillograms are symmetrical above and below the zero line, i.e. they indicate no difference due to the reversing polarity of the electrode and the work.

It would obviously be easier to observe any such difference as shown by the arc image with direct current, and it is recognized that the investigations described are incomplete without working on direct-current welding arcs.

*Quantity of deposit.*—One of the measurements which it is hoped to make with the help of the apparatus described is the quantity of iron deposited per unit of current and time, or per unit of energy in the arc. This again should be observed with both alternating and direct currents, and with varying electrode sizes and currents.

The literature of the subject contains a number of statements on this point, but they vary so widely that one can only suppose that they are made under widely varying conditions and are not comparable. Mr. Langdon Davies has kindly furnished some results of tests made by him. With a No. 8 electrode and direct current he found a deposit of 157·8 grammes per kilowatt-hour, the energy being measured at the input side of a motor-generator. With alternating current he obtained with the same size of electrode a deposit of 315·5 grammes per kilowatt-hour when the open-circuit voltage of the transformer was 55; and 351·0 grammes per kilowatt-hour when the open-circuit voltage was 45. The energy measurements in this case also were made on the input side of the transformer. As the energy includes the converting and transforming losses it is obvious that the deposit per unit of arc energy must be higher. The greater weight per kilowatt-hour with alternating current is naturally due to the fact that the motor-generator losses were much higher than the transformer losses. The improvement in depositing efficiency due to reducing the open-circuit voltage from 55 to 45 of course means smaller impedance losses between the transformer and the arc. These figures appear to suggest that the deposit per kilowatt-hour of arc energy is of the order of 800 grammes. Measurements with a considerable number of current values and electrode sizes will be necessary to establish the figure, which is hardly likely to be a physical constant in any sense. If it is the case that the iron is transferred as vapour, then there is a limit fixed by the vaporization heat of iron. Having found no record of a determination of this quantity, the authors cannot say what such limit is. Evidently, however, not all the iron volatilized at the electrode is deposited on the work, and the losses by oxidation, condensation, etc., are likely to vary to a large extent with the working conditions. Thus the oxidation losses should be higher with small electrodes than with large, supposing similar current densities, as the ratio of the surface to the mass of the vapour or arc body is greater in the case of the smaller electrodes and currents.

It may be observed that one instrumental difficulty in measuring the arc energy is that there are no integrating meters on the market for voltages in the neighbourhood of 20 volts, and an integrating meter (or the integration of voltage and current oscillograms) is the only practicable way of measuring the rapidly fluctuating energy in a welding arc.

*Conclusion.*—The authors cannot claim to have given definite answers to the question: What are the physical conditions of the iron welding arc? They have, it is hoped, shown ways by which some partial solution may be reached, and, if circumstances permit, they hope to pursue the inquiry with improved means and thus obtain some results of practical utility, and possibly of scientific value.

The work described has been done with home-made appliances, and under the limitations of a dwelling house. With laboratory conveniences and resources more definite results might have been obtained with less expenditure of time and labour.

The authors desire to acknowledge much assistance and encouragement from Mr. Langdon Davies, as well as from Major Caldwell.

## Discussion before The Institution, 14 December, 1922.

**Mrs. H. Ayrton:** I have been interested to see that this paper makes no mention of a back E.M.F. in the arc. When I first took up arc work in 1893, and for long afterwards, the idea that there must be a back E.M.F. at the crater to account for the sudden drop of potential there was practically universal. But from my experiments I concluded that what was called a back E.M.F. was really a resistance—not, as the author calls it, a contact resistance, but the resistance of a thin layer of carbon vapour covering the crater. It seemed to me that the arc exactly resembled the steam that issues from a kettle of boiling water; this is true vapour (and therefore invisible) only for a very short distance from the spout, but further away becomes condensed by cooling into a mist of droplets. In the same way the carbon vapour given off by the crater of the carbon arc, which is at the temperature of volatilization, is only true vapour while it is near enough to the crater to remain at that temperature. As successive layers of vapour are given off, the crater recedes further from the earlier ones, which, at some very short definite distance from it, must drop below that temperature and cool into a mist of droplets or particles—probably the latter. The vapour and mist column form the arc proper, sheathed in a flame due to the burning of the mist in contact with the air. Leaving out of account the small fall of potential at the negative carbon, the resistance of the carbon arc is, on this theory, the sum of the resistances of a thin layer of vapour of high specific resistance and of a column of mist of much lower specific resistance. In free air the cross-sections of the crater, the vapour and the mist are all smaller than they would otherwise be, owing to the cooling down of their circumferences. Except for modifications due to this cooling, the current alone determines the area of the crater, and this area fixes the cross-sections of the vapour and the mist. Thus, if there were no circumferential cooling, a change of current would, all other things being equal, produce an exactly proportional change in the cross-sections of the crater, the vapour and the mist; and, since the resistances of the two latter are inversely proportional to their cross-sections, the resistance of an arc of given length would be inversely proportional to the current, and thus the P.D. across it would be constant for that length. All this is changed, however, by the skin cooling, which, by making the resistance of the arc diminish more rapidly than the current increases, gives the appearance of a negative resistance, causing the P.D. across the arc to diminish when the current is increased, and vice versa. It is easy to see how this happens. Take $r$ as the radius that a cross-section of the arc would have if there were no skin cooling. Then the actual cross-section is $m\,(r^2-nr)$ or $mr\,(r-n)$, where $m$ and $n$ are constants. Clearly $r-n$ increases more rapidly than $r$, and therefore $r(r-n)$ increases more rapidly than $r^2$; that is, the actual cross-section increases more rapidly than it would in the absence of skin cooling. But the current is proportional to the uncooled cross-section, and the resistance is inversely proportional to the actual cross-section. Therefore the resistance diminishes more rapidly than the current increases. How much of the preceding applies to metal arcs I do not know, but it is worth while bearing in mind when experimenting with them. With regard to the transfer of material from one electrode to another, I have seen this happen in two ways in the vertical direct-current carbon arc. Sometimes small pieces break off the positive and drop on to the negative, or break off the negative and are carried by convection currents to the positive. This is accidental, but the second way is essential. When a fairly short arc is suddenly further shortened, a white-hot cap grows on the tip of the negative carbon, lengthening it for a short time. If hissing supervenes the cap grows into a "mushroom"; if not, it shortly disappears. The cap is mist, condensed by the sudden transference of the tip of the negative from a cooler to a hotter place. For a short time the negative retains the lower temperature and the mist in contact with it condenses. Only a short arc has a sufficiently steep temperature gradient for this to happen. As the mist was originally crater vapour this is a genuine case of transference from positive to negative, but it only occurs in the above special circumstances. There is much to be said on the point, but it would be out of place here. The transfer of material with metal arcs is altogether another question. Here, as the author points out, the vaporization is from a molten metal crater instead of from a solid one; in addition, the negative may easily be melted under the roasting of the crater, and so rendered particularly easy of transference. I would suggest that the superiority of the short arc in welding is due partly to the deep crater that a short arc always entails, making "penetration" easy, and partly to the negative being melted owing to its proximity to the crater. With an alternating-current arc this applies even more strongly than with direct current, because in this case as each electrode is positive in turn they must both necessarily be all the time in a molten state, and therefore easily transferable. May not this be the reason why Mr. Langdon Davies found that an alternating-current arc deposited practically twice as much per kWh as a direct-current arc? The deposit would probably be even greater with more rapid alternations. Half a dozen problems lie in this question alone. The author's paper shows that the metal arc offers a wide and fascinating field for research, and it is to be hoped that Messrs. Sayers will be able to continue their careful and well-thought-out experiments. Indeed, there is room for many investigators in a subject which promises such varied and rich results, both scientific and practical.

**Mr. H. M. Hobart:** During the past 5 years flux-covered electrodes have been almost exclusively used in this country, and no progress has been made with the introduction of the bare electrode. I consider that the author has made out a very good case for the use of flux-covered electrodes for the highest grade work. It is interesting to realize that in this country during the last 24 hours there have been melted up several hundred thousand feet of electrodes in making electric arc welds, and that during the same period in America a more or less similar quantity has been used. At least 95 per cent of the work in America has been done with bare wire, while in Great Britain flux-covered electrodes have been almost invariably used. During these past 5 years each country has known what the other has been doing, and each has been going its own way in the comfortable belief that its own method was preferable. I should like to point out the importance of different countries keeping in close touch with one another in their researches. For instance, British welding engineers are already satisfied that the use of the flux-covered electrode is correct in the majority of cases, and, consequently, although the paper is instructive it is not nearly as useful as it would be if it were presented in America. In the same way some American authors have shown to the satisfaction of almost everybody in America that the bare electrode is preferable; they say that the flux covering interferes with good work and involves greater cost. They also say that the bare electrode, in the hands of operators who know how to use it, gives the best results. If studied in this country it might be found that there is a field for the bare electrode in arc welding.

**Dr. C. Sharp:** I should like to say, as a member of many years' standing of the American Institute of Electrical Engineers, that it gives me very great pleasure to attend a meeting of this Institution. I have never heard a more interesting, a better presented and more instructive paper on electrical welding. We all wish to effect a more intimate tie between England and America, and to accomplish this result no means are more effective than electrical means.

**Mr. C. R. Darling:** Some years ago it was my privilege to preside over an Electric Welding Research Committee, which was under the auspices of the Admiralty. There I worked with Major Caldwell and others, and we kept in touch during the whole period with the corresponding committee in the United States. We certainly learned something from them, and I hope that they learned something from us. I quite agree that international research is very desirable. Very great advances have been made during the past few years in equipment and similar matters, but we do not seem to have got much further towards a proper understanding of the nature of the iron arc. Surely this question of fluxing the electrodes could be worked out and proved one way or the other. It seems extraordinary that in America 90 per cent of the work is done with bare electrodes at a cost much less than that in this country where flux-covered electrodes are used. It surely should not be difficult to discover whether an equally good weld cannot be obtained with bare wire; it is only a matter of having welds made by competent operators and testing them. A firm which possesses a research laboratory could take the two types of electrodes, make welds and test them to see if those produced by one method are as good as those produced by the other. Again, no mention has been made of the chemical side of the problems of arc welding. I have frequently seen welds made by the same welder on two pieces of plate cut side by side from a large plate with the same electrodes, but the tensile strength of one weld would be about 27 tons per sq. in., while that of the other one was only about 19 tons per sq. in. These differences are attributed to the presence of sulphur or occluded gases but were never properly explained. These points also could be cleared up by the research department of a firm, with the result that ultimately we should be able to put electrical welding on a much better basis, which would be all for the good of the work. In conclusion, I should like to refer to the projection of the material across the arc. In the case of an overhead weld the iron rises vertically from the electrode and is deposited on the work overhead, although the condensed vapour is heavier than air. The fact must always be remembered when discussing any theories of electrical welding. That is, I think, what the author meant when he said that there was definite projection.

**Captain R. J. Wallis-Jones:** The author states that owing to the war conditions the use of arc welding was very greatly extended, but I think one may say that electric arc welding was almost re-invented during the war. The paper is an excellent review of the present position of the arc with regard to electric welding. Further, it indicates the matters upon which further investigation is needed. I refer particularly to page 255, where the author asks: "In what state does the iron cross the arc?" Dr. Elihu Thomson, in a recently published article in the *Encyclopædia Britannica*, gives his view on that point as follows: "In operation the arc voltage may be from 10 to 20 volts, and the current traversing the arc may be from 80 to 200 amperes or more. The welding is attended by much spluttering and projection of fused and superheated globules of iron from the end of the wire electrode towards the cooler and heavier masses of the work pieces; in fact, the deposition of metal on the work is possibly due to a jet of iron vapour from the electrode wire carrying fused iron globules as a result of explosive boiling of the iron." The author also asks what is the distribution of voltage-drop in the iron arc, and what are the quantitative relations to electrical and other variables of this transfer of metal. I feel quite sure that we shall get some very useful information on these three points in the future. The author, later in the paper, refers to the use of alternating current, and the danger of shock. I think it is not fully realized how very dangerous it is under certain conditions to get a shock from a comparatively low-voltage alternating current. The Memorandum on Electric Arc Welding issued by the Home Office Factory Department states that in six years the number of fatal accidents from electric shock at 250 volts or less was 98 on a.c. circuits (one being from a welding set), and none on d.c. circuits. As pointed out by the author, fortunately at the present moment there are at least two devices which automatically limit the voltage, so that it is quite safe to weld in even such an undesirable place as the interior of a boiler. The author also refers to automatic arc-welding machines as being barely beyond the experimental stage. There are, however, two machines at present available, one of them being designed by the General Electric Company. It has an endless electrode, which is moved upwards and downwards by means of a motor actuating rolls which grip the electrode; the regulation is so perfect that the arc has, I understand, been operated for no less than 16 hours without interruption. It is claimed for this machine that it is very adaptable for welding thin sheet down to, say, No. 26 gauge. Another American machine, the Lincoln automatic arc welder, uses a carbon electrode, and the regulation of the length of the arc is also controlled by a motor. The traverse of the arc over the work is actuated by another small motor. I have seen samples of work said to have been done by this machine and they are very good, especially on thin material. The author refers to the fact that welding on thin sheets, etc., has not been very largely carried out by means of the arc process, possibly owing to the competition of oxy-acetylene welding and resistance methods. I should like to quote one or two figures of the rate of welding by the Thomson or resistance method. In the case of seam-welding two pieces of steel plate 0·036 in. thick, at the rate of 6 ft. per minute, such a seam 24 ft. long would cost 1d. to weld, for the energy only, when the cost of energy is taken at 1d. per unit. In spot-welding sheets of an added thickness of 0·16 in. at a speed of 70 spots per minute, 400 spots can be welded at a cost of 1d. with energy at the same price. These are fair figures. The very interesting apparatus which Messrs. Sayers have designed will, I feel sure, give much more information in the future about the action of the arc. In conclusion, I should like to say a few words in regard to the war services rendered by the author. While at the Admiralty, owing, I believe, first to the difficulty of getting oxygen for acetylene welding, the attention of the authorities was turned to the possibilities of arc welding. At that time the submarine menace was very serious, and therefore anything that could be done to facilitate the repair of shipping or to aid in the construction was of the greatest national importance. Major Caldwell did much valuable work for the Admiralty; he also visited America and, in collaboration with Mr. Hobart, did immense service in finding out what could be done to increase the use of electric welding. I should like to ask the author if he would be good enough to present to the Institution Library two books which he wrote at the time. The first is "Reports on Electric Welding and its Application to Ship Construction," United States Shipping Board (Emergency Fleet Corporation), and the other is the "Report on Applications of Welding to Ordnance Construction."

**Mr. W. McClelland:** As a colleague of the author at the Admiralty, I should like first to associate myself with Captain Wallis-Jones's remarks in regard to the valuable work which the author did during the war. He set up an organization and trained men all over the country, with the result that much very remarkable electric welding work was accomplished. As an example, a ship came into one of the shipyards very badly holed at the bottom, and it was necessary that she should be repaired quickly. The ordinary time for repairing that ship by riveting would have been 3 to 4 months, but with electric welding the ship went out to sea in 3 to 4 weeks, and for 18 months after that crossed the Atlantic to and fro regularly without a break. At a later stage the author assisted the U.S.A. authorities in regard to the development of electric arc welding for shipbuilding purposes. On page 253 he says: "Arc-welding practice is in advance of theory." He knows full well why this is so; it was absolute necessity; the development during the war was one almost of trial and error-elimination. It seems to me that the ideal electrode for welding should provide a molten vapour stream enclosed in an inert gas. The interesting experiments shown by Mr. Sayers this evening demonstrate that with the short arc the molten stream is enveloped in the molten flux from the flux-covered electrode. I think that is a very important point, and indicates a great advantage of the flux-covered electrode over the bare electrode. I should like to ask the author whether the experiments referred to in Appendix III were made with makes of electrodes other than the Alloy Welding Process electrodes, and, if so, whether he could tell us what makes and with what results. On page 255 he refers to the voltage, which he considers would produce what might be termed "porosity" defects. That again is, I think, a question of the particular electrode used. My experience is that this voltage with flux-covered electrodes would be from 35 to 40. As regards choice of current, it seems to me that, apart from the question of general distribution of alternating current, alternating-current welding has very few advantages. As to direct-current versus alternating-current welding—I say this with all deference to the experiments shown to-night and to what Mrs. Ayrton has so kindly stated—a.c. welds do not seem to be so uniform or so consistent in mechanical strength as d.c. welds. Certain tests which were carried out some time ago on steel plates with various classes of joints showed definitely that the d.c. weld was much superior to the a.c. weld. With alternating current, difficulty is sometimes experienced in establishing and maintaining the arc under a pressure of 90 to 100 volts, particularly at a low periodicity. The question of a.c. shock at this pressure to operators wearing coloured glasses and working on narrow staging at considerable heights on the side of an "earthed" ship in dry dock, is a serious one, and the automatic a.c. set referred to on page 263 appears therefore to be an interesting and useful development. With regard to the generator design, I am not sure that the importance of the automatic machinery for the production of a satisfactory weld has not been rather overstated. The author has furnished an excellent statement indicating the types of welding machines at present on the market. My experience for shipyard work is that the d.c. multiple welding set with a flat-compounded generator giving probably 60 to 70 volts when worked by a skilled operator produces satisfactory and consistent results. This type of machine is in my opinion the simplest and best to use, particularly where there is a possibility of extensions to a welding system, as with such a set one or many operators can work simultaneously quite satisfactorily. For welding work on the side of a ship in dry dock it is hardly practicable to have a portable automatic running machine for each operator; the first cost of such automatic machines would be high.

**Mr. E. B. Wedmore:** Mr. Addenbrooke suggested to me recently that had it not been for Ohm we should know a good deal more about insulation than we do. Ohm gave us a simple law of resistance. We say that conductivity is the inverse of resistance, and think that we know all about conductivity. I now suggest that had it not been for Mrs. Ayrton we should perhaps know a great deal more than we do about the metallic arc. We are tempted to think that Mrs. Ayrton has told us all about the arc, and we cease from making observations, whereas the success of the welding industry in the future will depend upon the attention given to the properties of the metallic arc. The author has maintained in the paper a very proper balance between our interests in the past and in the future. Whilst bringing to our notice details of the development of a large and important industry, he has devoted a large part of the paper to the subject of research, and the future rests on research. Mr. H. M. Sayers and his son are making a vigorous attack, but with very inadequate facilities, on some of the technical problems urgently awaiting solution. A sum corresponding to the saving already effected in carrying out any one only of the larger repair jobs which have been described to us, would provide the means for a comprehensive and productive research, which should repay the industry manifold. I feel sure that the Electrical Research Association would count it a privilege to place facilities for co-operative research at the disposal of the interested parties.

**Mr. H. M. Sayers:** I propose first to show three slides in connection with a.c. welding. The first shows the supply voltage, approximately sinusoidal. The second shows the voltage across the arc, and it will be seen that it is very different from the supply voltage. The rise and fall of the voltage are very sharp, and there is a double peak. The third slide shows the arc current. The curve is almost triangular, with a very considerable portion of zero current, and if the current curve is superimposed on the voltage curve it will be seen that the triangular arc peak must correspond to the valley between the double peaks of the voltage curve. I want to point out that the arc makes its own voltage curve, owing to the minimum voltage required for the arc current. Metal arc-voltage and arc-current curves with alternating current always seem to present these features. I have made some spectroscopic investigations upon the question of how the metal is transferred across the arc, and I find that at maximum current, i.e. when there is a blue luminous arc between the electrode and the work, the spectrum is to all intents and purposes an iron-arc spectrum, which contains a great many bright lines with some dark lines, particularly the dark sodium D line. At the phase of zero current the spectroscope shows other bright lines, i.e. not the iron-arc line. The brightest is the sodium D line. This shows that some of the iron is incandescent vapour. If it were wholly in a liquid state it would give a continuous spectrum, but as it gives a bright-line spectrum, and not a continuous spectrum, the inference must be that some part of the metal is in the state of gas. The fact that the dark sodium line is superimposed on the iron spectrum and a bright sodium line appears during zero current shows that the flux coating containing sodium produces an enveloping sheath round the iron vapour, and probably protects it from oxidation. It also, I consider, fulfils the very important part of forming a conducting bridge, or a bridge which will be conducting as soon as the voltage reaches a certain point and prevents the extinction of the arc during the zero periods. I suggest that, at any rate as regards a.c. work, these two functions of the flux are of the very greatest importance. With the help of Mr. Hamilton Wilson's tiny thermopiles I hope to explore the temperature distribution in the arc by getting radiation measurements in the arc image. As to the quantitative relation between the energy installed in the arc and the deposition, since I wrote Appendix III I have seen a statement in an American journal of the latent heat of vaporization of iron, in terms of grammes per unit of energy, from which I kWh should vaporize some 750 grammes. That is rather a lower figure than the 800 grammes which I have suggested. Most of the electrodes used in the experiments described in Appendix III were those of the Alloy Welding Processes, Ltd., and the Quasi-Arc Company. I have had to give more time to getting workable conditions than to making comparisons between different electrodes.

**Mr. P. M. Baker** (*communicated*) : The paper is particularly interesting to me as, during the later days of the war, I was able to make a few observations in connection with welding arcs in the establishments which we, of the Ministry of Munitions, set up to train men and women as operators for the welding work in which the author was then engaged. At that time the view was held that in the d.c. iron-iron arc the transfer of metal from electrode to work was an electrical function (analogous to some extent to the transfer in an electrolytic cell), and a.c. arcs were not, in consequence, favoured, particularly for upright and overhead work. We incidentally found that while it was a quite simple matter to train otherwise unskilled persons to do reliable welding with d.c. equipment in a comparatively short time, the work done by operators, trained on an "intensive" system, with a.c. equipment was much rougher and less satisfactory. The author's investigations and experiences seem to show that our ideas as to the force propelling the metal across the gap were wrong (we never held them very strongly), and he seems to favour the view that it is a thermal function—the metal travelling from a hotter to a cooler body. I should like to suggest that it may be a function of the difference between the *masses* of the work and of the electrode, respectively. From a scientific point of view this would be an interesting point to investigate, but its practical importance is not very great. In connection with single-welding d.c. outfits it would be interesting to know whether either the excitation or the magnetic clutch method of control acts sufficiently rapidly to maintain the arc current at anything like a constant value. Possibly the author in his reply could give recording-ammeter charts for some of these machines. Referring to the neat devices used by Mr. Sayers, I suggest that the results of his spectroscopic examinations would be of value, and the publication of his oscillograms would be helpful to those who are trying to visualize what happens in the a.c. arc. The two "shoulders" which appeared on the "steeple" of the current wave seem to indicate either a latent-heat effect or a curious resistance-temperature variation in the vapours at the moment of vaporization or quasi-vaporization of the iron. The superposition of the current and voltage oscillograms in correct phase relationship, if available, would probably help to decide which explanation was correct.

**Mr. W. H. Flood** (*communicated*) : The author has brought to our notice the successful development of electrodes for depositing copper, bronze and brass, and I am sure this will fill a long-felt want, as years ago we were asked if we could weld on copper or bronze pipe flanges by the arc process. Now that non-ferrous electrodes are available for this purpose, it will be possible to carry out quite a large number of repairs which have hitherto been next to impossible, e.g. locomotive furnaces, copper vats, etc., which must be repaired in position. I hope that the author will be able to supply us with data on copper welding, and, if possible, show some examples of actual work accomplished. As regards the various types of plant used and recommended by different concerns, the tendency appears to be in favour of alternating current, as the d.c. sets described which, I take it, are the best that designers can produce, are stated to be more or less complicated, and in consequence require a deal of care and skill to adjust in order to extract from them the exacting welding characteristics demanded by the metallic arc, whereas the alternating-current equipments are simple and free from such complications. As electric welding is now looked upon as a commercial proposition, the plant used must of necessity be quite free from uncertainty of action and complex adjusting switches and instruments, as the average welder is neither a mechanic nor an electrician, and, further, he cannot be expected to acquire sufficient knowledge to make delicate adjustments, even though he were so disposed, as in order to acquire the art of good welding he must devote the whole of his time to the business end of the electrode. To fit ammeters and voltmeters to welding sets for the guidance of welders is to my mind not only waste of money but absurd, as the man cannot possibly view these instruments when he is paying attention to the arc. The same applies to shunt regulators and other hand-operated devices which are found necessary in cases where motor-generator sets are employed. It is quite apparent that the majority of d.c. combinations are only suitable for single operators, and I doubt very much if any shipbuilding or engineering concern would be prepared to install a sufficient number of these sets to meet the demand of, say, from 10 to 50 welders, as my experience of plant of this description is that the possibility of breakdown is always present, and the upkeep of brushes and brush-gear is sufficient to put the proposition entirely out of court. To install one large unit with regulating resistances for each welder is equally bad, as the capacity of the generator must of necessity be more than double that required by the welders, on account of the heavy loss in resistances. Further, the cost of low-pressure cables between the generator and the various welding locations would be a considerable item which no purchaser could afford to ignore. With alternating current these difficulties are removed almost entirely, as the change from high pressure to the welding voltage is made by means of static apparatus, and no further adjustments are required when once the correct values are fixed, and in a well-known type of welding transformer the whole of the regulation required to give the correct welding characteristics is embodied in the design, and self-contained on one core. I refer to the Holslag transformer briefly described on page 263. With this apparatus the operator is not expected to have any electrical knowledge whatever, and, as it is not possible to destroy or burn out the windings during welding or by wilful means, the adoption of this welder is a sound commercial proposition and should find favour. This transformer must not be confused with the ordinary transformer and choke-oil combination, as the design is quite unique, and means are provided for obtaining full control of the correct heat or power required by any size or type of electrode, including bare wire. The transformer and choke-coil combination is analogous to the resistance on direct current so far as regulation is concerned, and its use is a step backwards in the progress of arc welding, as a separate reactance can only subtract from the voltage of the transformer, and such a system cannot supply the voltage regulation corresponding to the current fluctuations in the arc. Oscillograms show that were it not for the heavy flux coating on certain electrodes, a separate reactance could not hold the arc at the voltage employed, which means that there are periods when the molten slag is the only conductor and support for the arc with no iron vapour present, and this condition encourages slag inclusion which is a very bad feature. Also, the proper variation and separation of the voltage factor cannot be obtained with the transformer and separate reactance. The only regulation obtained is that for constant current, whereas the control of power is absolutely essential for melting metal efficiently. For correct welding the power must be kept constant, and means provided for automatically adjusting the voltage instantly the current varies or the arc has a tendency to die out. This is called a "guardian" voltage, and is always present with the Holslag system and ready to act instantaneously when required to support or adjust the power for which the apparatus is set. To meet Home Office regulations this set is fitted with a special safety contactor device operated by a 25-volt winding, which ensures that the operator is protected from all possibility of receiving a shock due to the open-circuit voltage which is considered dangerous. This contactor is operated automatically on striking the arc, and drops out immediately the arc is broken. It will be readily observed that with apparatus of this description there is no limit to the number of units which can be installed, as in the majority of cases works have an ample supply of alternating current and substantial transformers, and by equally distributing the welding sets across the phases the load is balanced within limits, and no complexities, other than those present when the first few sets are put into operation, appear. The efficiency of such a system is good, and as the upkeep of plant is reduced to practically nil I think it will be agreed that the alternating-current proposition is to-day in advance of any direct-current scheme.

**Lord Angus Kennedy** (*communicated*): In the discussion of the use of flux-covered versus bare metal electrodes it appears to me that sufficient stress has not been laid upon the important part that the flux plays in alternating-current welding by protecting the weld from the air. If welders attempt to use bare electrodes with alternating current, consistently satisfactory results cannot be expected.

**Mr. R. S. Kennedy** (*communicated*): I consider the paper to be an able exposition on plant and materials as at present available. On page 258 the author quite rightly remarks that the automatic arc welder has not yet arrived. My own experience in actual working has been entirely with direct current, and we find the difference in temperature of the poles to be a distinct advantage. We also find a voltage of 45 on a level-compound machine to be sufficient for our work, and considerably higher currents than 200 amperes can be handled. On the same page the coating of the electrode also is referred to; I prefer a coating that fuses at a slightly lower temperature than the iron electrode, so that the tip is exposed and the man can better watch his work. This is particularly necessary in overhead work. I do not consider that the slag method is an advantage or that it is necessary with fully trained welders.

**Mr. H. Ogden** (*communicated*): I think that the solution of the transference problem lies in the direction of a consideration of all the forces acting in the region of the arc, for we must admit no mystery in the transference of metal. What are these forces? First, there is gravity and this certainly assists in the transference of metal in downward welding, which is thus made easier than overhead welding. Secondly, there is the "pinch" effect of an electric current and I believe this to be important. In induction smelting furnaces the "pinch" effect causes a rupture in the liquid metal when the current density exceeds a certain value. In the arc I believe that this effect helps to detach drops of molten metal from the tip of the electrode acting against the force of surface tension in the molten drops. Thus this effect creates drops of metal which under other forces then travel across the arc to the larger pole. The main factor which draws the drops to the work is surface tension coupled with a greater vapour pressure at the electrode tip than near the more massive work. What I have just mentioned deals with the transference of the larger drops which in welding can be seen crossing from electrode to crater. With regard to other forces exerting an action tending in the same direction, there is first the condensation of metal vapour on the more massive work. Owing to the greater thermal conductivity of the latter, the vapour pressure in its neighbourhood must be lower than that in the neighbourhood of the electrode tip, so that the conditions are correct for the vapour wind of which Mrs. Ayrton spoke and a certain, if small, amount of metal is transferred in this way. Another force always present is the electrostatic field, about 100 V/cm, between the poles of the arc. The force of gravity acting on a small drop of diameter $r$ is $32\,000\ r^3$ dynes (approximately). The electrostatic force on the same drop is $r/45$ dynes and thus, when $r$ is less than 0·001 mm, the electrostatic force exceeds gravity and these very small drops would invariably travel to the larger pole where, owing to the geometry of the arrangements, the conditions are not favourable for the production of drops. It has been suggested by Prof. Hudson in America that the liberation of occluded gas is instrumental in assisting the transference of metal, but this does not agree with my observations. A wire freed from occluded gas runs smoother and with less splutter than one with occluded gas. In the projected arc exhibited by Mr. Sayers occasional large drops of metal or slag were flung well to one side. Occluded gas, or gas liberated from the heated flux, is probably responsible for such action, because it must be allowed that such gas liberation acts equally in all directions and must tend to blow metal away from the work. Another view, which at one time held some adherents, was that the metal was carried by the current. As the author pointed out, metal is transferred from the smaller to the larger pole, irrespective of polarity. Further, if the current were responsible for the metal transference there would be some quantitative relation between deposit and current, as in an electrolytic cell. No such relationship exists, and so the idea that the metal is carried by the current must be abandoned. Finally, in my opinion, metal is transferred from the smaller to the larger pole chiefly through the action of surface tension, local differences in vapour pressure and the "pinch" effect of an electric current all acting together. In a second degree it is transferred from the smaller to the larger pole by the action of the vapour wind mentioned by Mrs. Ayrton, and by the action of the electrostatic field on very small drops. Before concluding, I should like to refer to the carbon mist mentioned by Mrs. Ayrton. Violle * has measured the temperatures in the carbon arc, which he gives as 3 500° C. for the anode crater, 2 700° C. for the cathode, and higher still for the arc itself. I believe these observations have been confirmed by subsequent workers, and so it appears unlikely that carbon vapour from the positive pole should condense to a solid particle mist in a region of higher temperature than that at which the vapour came into existence. The clear space and misty region observed so beautifully by Mrs. Ayrton are probably susceptible to another explanation, as similar appearances are observed in the discharge of electricity through gases at low pressures.

**Mr. D. T. Smout** (*communicated*) : The paper undoubtedly reveals the great divergence of opinion which it is possible for those interested in the practice of the art to possess. The author has shown, however, that good work can be done with many different types of plant and equipment. As the skill and reliability of the artist is the predominating factor in determining the quality of the work executed, it follows that the average quality of the work done falls short of the best possible. In deciding which type of apparatus and equipment is the best, it is therefore necessary first to take the human element into account, and then aim at developing a plant and system of welding as theoretically sound as possible. To conform to this principle it is advisable to disabuse oneself of the idea that an electric arc welder can be at once a combined electrician, metallurgical chemist, smith, etc., nor should he be expected simultaneously to make various adjustments to plant and perform the art of welding. The essential qualifications of a welding operator should be the capability of maintaining a continuous arc of more or less constant minimum length, and the possession of the faculty for recognizing the phenomenon of burning metal. It is well known that with the methods at present in vogue the metal deposited when the arc is first struck is faulty, owing to the fact that the electrode metal is deposited before any crater is produced in the work. For good work it is necessary, therefore, to deposit the first ½ inch or so of electrode metal outside the "V," and the remainder continuously without sticking and restarting. Given electrodes of uniform quality, and electrical apparatus supplying the correct characteristics, an operator with the qualifications mentioned above is not difficult to find. In considering the question of electrodes, irrespective of the type (bare, thinly coated, medium coated or heavily coated), it is necessary that for perfect work two conditions must be present. First, the quality of the electrode metal, and the quality, concentricity and thickness of the coating should be uniform throughout the length of the electrode, subject to certain reservations with regard to concentricity and thickness of coating. Secondly, the physical conditions of the electrode in close proximity to the arc should remain constant, also subject to certain reservations. With regard to the first condition, from personal observation I have found little trouble on the score of lack of uniformity in the quality of electrode metal, but have found that many types of coated electrodes leave much to be desired as regards uniformity of the coating. One well-known type of electrode in particular invariably reveals a bad spot about ½ inch from the commencement, owing to a failure on the part of the manufacturer to preserve perfect uniformity in this respect. In depositing this particular electrode the arc is invariably destroyed when this bad spot is reached. With regard to the process of covering heavily coated electrodes by means of asbestos yarn, I should like to suggest that this method does not tend to preserve the stability of the arc. It is well known that when an arc is maintained at the end of an electrode coated on half of its cylindrical surface only, the axis of the arc is not maintained in line with the axis of the electrode, but takes up a position away from the coating; it is easily conceivable, therefore, that with an electrode produced in the manner criticized the axis of the arc will be deflected away from the existing position of the overlapping yarn, and will rotate as the coating is removed. This phenomenon is referred to in Appendix III. In practice the electrode is seldom held normal to the surface of the work, and there is therefore a periodic distortion and a variation in the virtual length of the arc, which does not tend to give stability. This points to the importance of improving the present methods adopted for coating heavy slag-depositing rods. With reference to the physical conditions of the electrode in close proximity to the arc, it is obvious that, owing to the $I^2R$ losses in the electrode itself and to heat conduction along the length of the electrode, the temperature of the wire itself must be increasing. In practice the value of the maximum current which can be used with any particular size of wire is limited, at least on electrodes of sizes below No. 5 S.W.G., by this temperature-rise. In general, for all types of electrodes and in particular for bare and thinly coated rods, more efficient work would be performed, and the rate of deposition increased, if the wire were tapered so as to reduce this temperature-rise. For instance, given a wire 16 in. long, tapered from end to end, say from No. 10 to No. 8 S.W.G., it will be possible to deposit this with a current of approximately the same value as is at present used with an ordinary untapered No. 8 rod. The tapered wire mentioned would be roughly equivalent to a No. 9 S.W.G. untapered rod, and it is obvious that the average current density will have been increased without the detrimental overheating of the electrode. I should like to draw the author's attention to this matter, as he may not be aware that a certain firm is at present carrying out investigations with a view to putting tapered wires of this description on the market, and his views on such a proposition would be of considerable interest. With regard to the ideal characteristics necessary in the welding circuit, it is important that the whole matter be reviewed from what is known of the arc performance under high, open-circuit voltage conditions. First, from the physical aspect of the subject of metal deposition by the arc, it appears that the conditions ideal for arc stability are those giving constant watts in the arc within the limits fixed by the open-circuit voltage consistent with the safety of the operator, and excessive short-circuit current causing the electrode to "freeze" to the work. I suggest that, given a momentary condition in the arc when the vapour mass decreases in conductivity, it is necessary that energy be supplied to maintain the original rate of transference of metal across the arc, otherwise the trouble can easily be cumulative, resulting in the dying out of the arc. Another matter which appears to me to be of great importance in considering the stability of the arc is the ability of the apparatus or machine to counteract instantaneously sudden arc fluctuations. If it can be accepted that there are present in the arc conditions which give rise to high-frequency current fluctuations, I would suggest that the performance curves of various welding machines given in the paper are no guide to the actual ability of the plant to maintain a stable arc. The conditions set out above in regard to plant, electrode and operator call first for plant and electrodes which give a stable arc, and the broad characteristics of the machine are of secondary importance, as without stability the results of a non-stable arc wipe out all the beautiful points which might be claimed for first-class electrodes or welding plant. In conclusion, I should like to refer Messrs. Sayers to the reference made by the author to Mr. Holslag's paper given before the American Institute of Electrical Engineers on his welding transformer. I would suggest that in comparing their oscillograph records with those obtained by Mr. Holslag with his transformer, Messrs. Sayers will find the reason why the stability of their arc was so poor. If they replace their welding apparatus by one more suitable, and the electrode feeding mechanism by an average operator, I can assure them that they will get a more stable arc with bare wire.

---

* *Comptes Rendus*, 1892, vol. 115, p. 1273.

**Major J. Caldwell** (*in reply*): It has been my endeavour in the paper to show that suitable apparatus, equipment and welding materials are now available for use. The conditions for using these to make good welds are known, and whilst these conditions include skill, experience and careful use of the apparatus, they are not more difficult to fulfil than those of many established industrial operations: it is at least not more difficult to train a reliable electric welding operator than a reliable welding smith.

I believe that the only possible means of permanently establishing electric welding as a standard method of construction is for the present manufacturers and designers of steel structures, with their special knowledge and experience as a guide, to indicate how electric arc welding, with its recognized advantages, can be applied to best advantage to secure satisfactory results at competitive cost.

The statement in the paper with regard to bare and flux-covered electrodes is a reflection of general opinion, but my own belief, based on experience with both methods, is that bare-wire welds are inferior in strength to those made with covered electrodes, and both Lloyd's and Admiralty specifications support this.

Mrs. Ayrton's views in regard to arcs must command respectful attention, and I am much gratified by her comments and suggestions. Perhaps the difference between my "contact resistance" and Mrs. Ayrton's "very thin layer of (carbon) vapour" to account for the constant term in the potential difference of an arc between electrodes of a given material, is not very great. If the electrode material is such that it remains in the state of vapour right across the arc—which seems to be the case with iron—contact resistance may better fit the facts. I would suggest that in any case this constant potential difference is connected with the energy absorbed in the vaporization of the material. Mrs. Ayrton doubts the real transfer of metal across the arc, but, in welding, the work gains weight and the electrode loses weight. Mrs. Ayrton agrees with the views expressed in the paper, viz. that there is condensation of the vapour. The suggestion that welding is easier at high frequencies is borne out by some experiments at 200 periods per second, which showed that the manipulation of the arc is decidedly easier at that frequency than at 50 periods. Whether the weld is better remains to be proved.

Mr. Hobart's suggestion that British and American welders should probe to the bottom their difference in practice, i.e. the question of bare versus flux-coated electrodes, is excellent. It can only be done by research, as there are many variables involved in practical welding. Mr. Hobart has himself done much to stimulate arc welding research in the United States, and Dr. Sharp gives rise to a hope that he and Mr. Hobart may do something on the other side to initiate such combined research on this and other unsolved problems of arc welding.

Mr. Darling suggests that tensile tests of welds may be of value in deciding between bare and covered electrodes, but the example which he gives of the difference between welds made by the same welder, with the same electrode on the same plate, shows that tensile-test results have to be treated with caution. As the result of many tests, including tensile tests, both the Admiralty and Lloyd's specify flux-covered electrodes for strength welds. I agree with Mr. Darling that there is room for research into the chemistry of arc welding, and also that there is abundant evidence of definite projection of the iron across the arc. Visible drops of molten iron do fall from the electrode on to the work in horizontal welding, but they do not weld into the work properly, and are generally oxidized. They are more in evidence with bare than with flux-covered electrodes.

Captain Wallis-Jones's statements as to the costs of the resistance welding of thin material are very welcome. Spot and seam resistance welding are well established as valuable manufacturing processes, but there are occasions when arc welding on thin material is of value because the work is not accessible to a resistance welder or there is not enough of it to justify making a suitable machine. I have already sent to the Institution Library the two Reports mentioned by Captain Wallis-Jones, and I have to thank him for his generous remarks on my work at the Admiralty.

I am glad that Mr. McClelland has stated so clearly the advantage of flux-covered electrodes in providing a sheath of inert gas or liquid slag surrounding the molten or vaporous iron. As regards the relative merit of a.c. and d.c. welding, a good deal has been done since the date of the tests mentioned in determining the practical conditions for making a.c. welds, and my present opinion, as stated in the paper, is that intrinsically there is little or nothing to choose between the two methods. The striking of the a.c. arc is a little more troublesome until the knack is acquired. The voltage mentioned by Mr. McClelland for bare iron electrodes seems very much on the high side, if he means the voltage across the arc. In the automatic welder exhibited at Olympia by the B.T.H. Co. it was noteworthy that the voltmeter across the arc gave a very constant reading of only 15 to 18 volts. Undoubtedly the electrode material has an influence on the voltage-range consistent with sound welds.

Mr. Wedmore's offer of the assistance of the Electrical Research Association is noted with thanks, and it may possibly be accepted in the future.

Mr. Sayers's oscillograms show very clearly how the arc characteristic makes its own voltage curve, and the spectra described appear to prove the value in a.c. welding of a flux coating which provides conducting vapour of lower temperature than that of the iron, and therefore acts as a bridge across the current intermissions.

The reference to the vaporization heat of iron is to be found in a paper * by Mr. J. W. Richards, which gives the value of 1 110 calories per gramme for the latent heat of vaporization of iron, and the boiling point of iron as 2 698° (abs.). The latent heat value corresponds to 781 grammes evaporated per kilowatt-hour.

In reply to Mr. Baker, oscillograms of the d.c. welding arc current show variations much too rapid for either excitation or clutch regulation to follow. The inclusion of some reactance in the steadying resistance greatly reduces the amplitude of these rapid variations.

Mr. Flood quite rightly considers the successful arc welding of bronze and copper to be a very important development. In this branch, again, practice is ahead of theory, and I cannot at present supply more data. A number of samples of work accomplished were on view at the meeting, and can be seen by anyone sufficiently interested to communicate with me. Mr. Flood's views on the advantages of a.c. versus d.c. welding plant are quite sound, but, as the discussion shows, there is a considerable body of adverse opinion in respect to the relative quality of a.c. and d.c. welds.

Mr. Kennedy thinks that the electrode coating should fuse at a lower temperature than the iron. It should not be much lower, or the electrode will oxidize at the exposed tip. On the other hand, it should not be much higher, or the electrode will " cup " deeply, unless the covering disintegrates instead of fusing. This disintegration actually occurs with some flux compositions and is easily seen with the projection apparatus.

Mr. Ogden's discussion of the mechanism of the transfer of metal across the arc raises more points than I can deal with in this reply, but on the whole I think it favours the view that a difference of temperature between the electrode and the more massive work is a necessary and even the chief condition of the transfer. The electrostatic force is certainly one factor to be considered. I agree with him that the explosion of occluded gas is not the cause. The drops passing to the side of the arc as seen in the projection are certainly masses of molten flux.

Mr. Smout's suggestion in regard to the tapering of electrodes is new to me, and there would have to be clear proof of considerable advantage in working to justify the extra cost of manufacture. His criticism of the instability of the arc as shown by Messrs. Sayers can be met by the statement that the supply conditions at the Institution were not altogether favourable. In their own test-room it is quite usual for an entire electrode to be consumed without any interruption.

I feel that the members of this Institution are best

---

* *Transactions of the American Electrochemical Society*, 1908, vol. 13, p. 447.

qualified to assist in the development and to appreciate the considerable future of electric arc welding, not only as an addition to the load factor of power supply undertakings, but also as an outstanding example of the industrial usefulness of electricity.

The question of unemployment very materially affects members of the Institution, and I therefore welcome the reference made by Mr. Baker and Mr. McClelland to the training of electrical welders. Electric welding has been advocated for the following reasons :

(1) It effects repairs which would otherwise have been impossible.
(2) It provides water- and oil-tight jointures.
(3) It increases production in the manufacture and erection of steel structures, owing to the speed of working and the ease with which unskilled labour can be utilized to secure maximum strength.
(4) It settles labour disputes by providing another method of construction and repair.
(5) It provides employment for disabled Service men.

In addition to the training of welding operators at the Royal Dockyards, shipyards and engineering works by the Admiralty, facilities were provided towards the end of the war by the Ministry of Munitions at Loughborough, Birmingham, Acton and Bradford for the instruction of discharged soldiers to a limited extent. It was proposed to increase the capacity of these training centres and to incorporate a much larger scheme including Glasgow and Newcastle. I very much regret that this proposal was shelved on the cessation of hostilities and, as I cannot think of any craft at which proficiency can be secured so quickly, I submit that the matter should receive more consideration now by the Ministry of Labour, and for my part I would gladly hand them the information which was prepared for the purpose in 1918.

In conclusion I am pleased to acknowledge that the important points in the paper have all drawn information and criticism from qualified contributors, and I hope that the interest shown is indicative of speedy future progress in both the theory and practice of electric arc welding.

---

# ADDRESS TO THE LONDON STUDENTS' SECTION.

By C. H. Wordingham, C.B.E., Past President.

(*Address delivered before the* London Students' Section, 10*th November*, 1922.)

It gives me great pleasure once more to address you. Probably none of those present to-night have heard the addresses which I have given to this Section of the Institution on previous occasions, but I will, none the less, try to avoid repeating what I have previously said.

Most of those present are in the habit of listening to a large number of lectures on scientific and technical questions delivered by extremely able professors, and, instead of endeavouring to emulate them, I propose to speak rather of engineers than of engineering.

It is now some 35 years since I passed from the Student to the Associate Member class. As one gets older, and sees the younger men with their feet just set on the long ladder which one has traversed oneself, one is filled with sympathy for them and a longing to help them by pointing out the rotten rungs, the places where an alternative ladder presents itself, and the narrow plank in space that must sometimes be crossed.

Most often youth is impatient and resents any attempt at interference with its own judgment, but I must risk this possible hostility and do my best according to my lights.

One of the greatest temptations which besets those who study science is a tendency to cocksureness and a contempt for those who, in the earlier times in which they lived, were ignorant of present-day knowledge and achievement. The purely scientific man is prone to formulate theories, to test them at a few points, and then to speak of them as ascertained truths. The young student is impressed with what he takes for the triumph of intellect, and is intolerant of those who are somewhat sceptical of the new-found truths and who cling rather to what these old-fashioned people regarded as eternal verities, matters on which the young student is often ill-informed, and which he is apt to dismiss as contemptible trash which can have no place in his intellectual and scientific mind.

In successive years one sees examples of this attitude of mind in meetings of the British Association, that curious conglomeration of picnickers, some of whom are in the forefront of science, some ultra-scientific in a field of microscopic extent, and many of whom are of the gullible general public, open-mouthed to swallow any modern wonder at its face value, having barely a smattering of scientific knowledge. Year by year we are treated to elaborate speculations as to the origin of things, or are told that man with all his attributes is merely a cleverly made machine. Newspaper articles solemnly warn the churches that they must reconsider their position, as though the speculations reported were ascertained facts. Next year some other learned pundit brings forward some other wonderful theory and the discredited one of the year before is forgotten; once more the newspaper takes up its cocksure attitude as to all old-fashioned ideas being exploded. One and all of the speculators, however, forget to explain where the actual origin came from and who designed the clever machine.

Another aspect of modern conceit is in respect of modern invention. I am second to none in my admiration of the cleverness, perseverance, and hard work devoted to the making and perfecting of modern inventions, but I do feel a very serious doubt as to whether mankind is really the better or the happier for many of them. The vast majority of modern inventions are devoted to speeding-up things; the bicycle enabled a man to move faster than he could by running; the motor easily outstripped the bicycle, and the flying-machine the motor. The result is that everyone by the use of these machines can do more in a given time than he could before their advent. Is he better in health or happier in mind for the facilities he possesses? Is it not a fact that the speeding-up of things has increased the number of nervous breakdowns, a disease unknown I suppose to our grandfathers, and has made the lives of many one long round of incessant, anxious work? The telegraph, the telephone, the railway, the ocean liner, all marvellous instances of human ingenuity, have the same tendency, and in addition they have taken much of interest out of the world by bringing all the more important towns to one dead level so that travel has lost most of its interest.

The much vaunted printing-press, while undoubtedly effecting an enormous amount of good, has of late years had much of this good discounted by rendering possible the daily and weekly newspapers (I do not refer to the technical journals) which consist chiefly of a mass of garbled statements, such statements having little relation to truth and being generally paid for by a political party or by people with axes to grind or things to sell. No sensible person will ever place the slightest reliance on anything which he reads in a newspaper published at the present day, without independent corroboration.

Probably, without exception, each one of my audience has by now classed me as a gloomy or foolish pessimist, as a reactionary idiot, or an old fossil in his dotage—I do not mind.

Admittedly I have given you only one side of the picture, and I further admit freely that I always travel by the fastest express trains and the fleetest motors, make every use of the telephone and telegraph, do everything electrically that I can, and as far as possible am in two places at once and get 25 hours into the day. All I want to impress upon you is that I do not believe I am any better in health or happier for it all, but I must do it because I live in the century which, as Carlyle would say, "flatters itself it is the twentieth."

I want to convince you, if I can, that all these inventions and discoveries are merely froth on the sea of life. They are here to-day and superseded to-morrow, and I believe that many of the achievements in ancient times, effected under civilizations of which there is now no trace or only traces of the slightest, were in fact more wonderful than our own.

I do not think that I can express better what I have in mind than by quoting a few lines of a poem by Campbell, with which some of you may be familiar, entitled "The Last Man." The poet is picturing the end of the world as seen through the eyes of the last survivor of the human race, and in addressing the sun he says:—

> "What though beneath thee man put forth
> His pomp, his pride, his skill,
> And arts that made flood, fire and earth
> The vassals of his will—
> Yet mourn I not thy parted sway
> Thou dim discrownéd king of day,
> For all those trophied arts
> And triumphs that beneath thee sprang,
> Healed not a passion or a pang
> Entailed on human hearts."

The things which really matter are the abstract qualities of man—not his machinery, but what we old-fashioned people call his soul and spirit, his love of truth, of justice, of honour, his capacity for love, sympathy, self-denial.

There is no denying that the world is in a very parlous state, and we are one and all suffering from it in one way or another, in greater or lesser degree. I believe that the main reason is that mankind has lost sight of the things that matter and has magnified material activities to such an extent that they have usurped the place of the vital essentials of life.

One important direction in which invention has been most prolific and successful is that of labour-saving appliances. Do not mistake me; under the conditions which we have created for ourselves to live in to-day, such appliances are absolutely essential. They have been invented, we must reckon with them and use them, otherwise we must go down in the fight. I believe, however, that, so far as the formation of human character and the promotion of human happiness are concerned, they are almost wholly bad. They have taken the interest out of life for most of the workers. It is true that each man can produce far more in quantity, and to a much greater degree of accuracy so far as dimensions are concerned, by making one small part of an article than by making the whole thing. But what is the price to be paid? An utter absence of any pride in his work, the elimination of all interest in it, with the result that instead of the craftsman's satisfaction in the designing and successful construction of some article of beauty or utility, there is a dull or sometimes fiery resentment at having to devote so many hours a day to repetition of certain motions of the limbs calling for little or no skill.

Another, and even greater, evil is the aggregation of these human automata in large numbers under an organization which is as dead and machine-like as the tools they operate. Just as no man can add a cubit to his stature, so no man, singly or in the mass, can change the nature of the human being which is not an automatic machine but an assemblage of passions and sentiments of infinite variety of both kind and strength. We are suffering now acutely in industrial unrest resulting from this callous disregard of those laws of the universe which we may investigate but may not alter.

A man is endowed with faculties, powers which enable him to work, to contrive and to execute, and he is so constituted that he must have contact with others of his kind on which to exercise his human attributes. Only in proportion as he has the opportunity of exercising those faculties and powers will he be happy and healthy in mind and body. Deny him that exercise and he becomes a monster and the world a terrible place to live in.

Now, you will ask, what has all this to do with engineering, and, more especially, with the engineering student? I will tell you. Most of you are starting, or have just started, on your careers: what is necessary for your success? Naturally you must be equipped with the very best scientific and technical education you can obtain. Subject possibly to the exception of a few brilliant men with inborn genius who do arise from time to time, the day has gone by when the man who picked up his knowledge as he went along can hope to attain a good position as an engineer. Every young man entering the profession must make himself acquainted with the present state of knowledge in the various branches, and must have a special knowledge of the one in which he proposes to practise. This knowledge, however, as I have said elsewhere, is only his bag of tools. The finest kit in the world will not carry him far if he does not know how to use them. It is in the use of them that the human element comes in and that the exercise is called for of such abstract qualities as sympathy, kindliness, consideration, firmness, fairness and honour. These are the determining factors. The works manager who has favourites, who tries to get the better of his men, who bullies and insults those under him, or truckles to a dishonest employer by allowing scamped work, will never be a success. The adviser whose advice is coloured by his own self-interest, or who is open to bribery, may make money but he will never attain an honourable position. The staff man whose heart is in his amusements and who only does so much work as he is compelled, doing it as an uncongenial task to be put out of mind when he puts on his hat, will find his promotion slow and his change of employment frequent.

It is the man himself who counts. He must have his equipment of knowledge and skill, but also he must be able to use that equipment.

Just one word on the subject of work. The fashion of the day is to exalt amusement as the chief aim in life, and to represent work as a task to be reduced to the shortest period possible. So far have things gone that a man's opportunity to work is in certain directions forcibly limited by Act of Parliament. Work is essential to our existence, and it behoves each one of us to find out for himself what kind of work he is best suited to perform and then to find means to make it his vocation. Ordinarily, many drift into their life's work, but I imagine that few drift into engineering; most enter the profession from deliberate choice, presumably because it attracts them. Fortunate indeed are they if they have correctly gauged their inclination, for the true engineer needs no artificial amusement, his work is his hobby and is seldom out of his mind, even when taking, as he should, legitimate relaxation.

Most of us must have asked ourselves at one time or another: What is man's ultimate destiny? What are we here for? Each must find his own answer. I suggest that one of the most important objects in life is the formation of character, and if this be so, every thought, every action has its effect, indelible and permanent. Every job carried out assumes then an importance far greater than its intrinsic worth would give it. The primary thought in every engineer's mind should be: "Will this thing which I am carrying out be to my credit as an engineer or to my discredit? Suppose the work which I am doing to-day, and which will soon be out of sight, is unearthed 20 years hence, will its discoverer say of it that the job was well done or scamped?" I know of no pleasanter sensation than that of revisiting something carried out years ago and being able to tell oneself that it has stood the test of time and is still functioning well. I would say to each of you: "Try to do every piece of work primarily for the work's own sake and for the sake of its effect on your own character. The pecuniary reward in any one instance may be small or great, but in the long run that too will be added to you."

This country, perhaps more than many others, is suffering from a disregard of the principles which I have been trying, very lamely I fear, to enunciate. Work is in very bad odour just now. The doctrine that happiness is the be-all and end-all of existence is screamed at us from numerous quarters. Happiness is confounded with amusement, leisure and the possession of money, all of them hideous counterfeits of the real thing. A duty accomplished, a difficulty successfully overcome, a job well done, these are the things which confer real happiness, happiness worthy of man with his infinite possibilities and responsibilities.

Duty is a word seldom heard nowadays; "Rights" has taken its place. Read the letters written a century ago and you will find the word "duty" constantly in the mouths of our forefathers. Who built up our great Empire? The men whom England expected would do their duty, and who did it. Who are endangering that Empire? Those who preach pleasure, falsely so-called, as the greatest good, who honour a man according to the amount of money he possesses however he may have gotten it, and who call evil good and good evil.

Each of you young men has it in his power to work for his country, as so many of your number died for it only a few short years ago, and to help so to direct the course of events that this great nation of ours shall go up and not down in the scale of humanity and in its upward progress shall be an agent for the uplifting of mankind at large.

# ADDRESS TO THE SCOTTISH STUDENTS' SECTION.

By J. F. Nielson, Member.

(*Address delivered before the* Scottish Students' Section, 17*th November*, 1922.)

To all Students of this Institution I would emphasize the advantages of attendance at, and participation in the meetings of the Students' Sections. There is nothing more conducive to clear thinking than the writing of a paper. It need not be the account of original research work accomplished by the writer; indeed few of you will have an opportunity to present such a contribution. In this connection it is very gratifying and indeed encouraging to learn that one of the Students connected with this Section, Mr. J. C. Stewart, who contributed a paper last session on "Electricity in Mines," has been awarded by the Council a Student's Premium. It is to be hoped that at least one paper to be read before this Section during the present session may be similarly rewarded. Again, by joining in the discussions—and you need not fear to express your opinions or show an appetite for information on any subject for fear there may be a "chiel amang ye takin' notes," or if there is, "he'll no prent it"—an excellent training in self-assurance as to one's ability to give expression to one's ideas is obtained. Such a training will be found to be invaluable in years to come. Then again, at meetings such as these, opportunities occur, sometimes quite unexpectedly, of making the acquaintance of contemporaries, the consequences of which may be far-reaching in influencing your future and in moulding your careers. Do not, however, let these ideas, however admirable and desirable they may be, dominate your thoughts too exclusively. One of the finest definitions of a gentleman I have ever come across is: "he who puts more into life than he takes out of it." As members of this Institution you will have frequent opportunities of putting this virtue into practice—giving more than you get. As engineers you will, if you properly apprehend your calling, be assisting much more effectively than the politician in the creation and fostering of such an ideal atmosphere for human society as—to quote the words of Edmund Burke—is grounded in "a partnership in all science; a partnership in all art; a partnership in every virtue, and in all perfection." Such surely is the ideal towards which statecraft should be directed if the future peace of the world is to be maintained.

I am well aware that a proper apprehension of the calling of the engineer by those who practise it does not always exist, and that there are those who come into close contact with the forces of Nature without being affected thereby; still, I think, to most men such an experience must arouse feelings of the puniness of mankind and the boundless possibilities for discovery in still untrodden fields.

This year (1922) is memorable in the history of electrical engineering and of that particular branch of it to which our great citizen, Lord Kelvin, contributed so much of the fruits of his genius. I refer, of course, to the Jubilee of the founding of the Institution and of the Eastern and Associated Telegraph Companies.

The Institution was really founded earlier than the 28th February, 1872, but that was the date when its first Meeting was held. Electric telegraphy was then, as Dr. Kennelly says, mighty both by land and sea. Sir James Anderson, one of the pioneers of submarine telegraphy, presented a report to the Statistical Society in 1872, in which he stated that the total capital invested in submarine telegraph companies amounted to £10 230 370, and the total length of cables laid was 37 795 miles. These figures are very significant of the progress made by the telegraph industry since the first Atlantic cable was laid in 1858, only 14 years previously. It was even more striking to read a few months ago, when the Eastern and Associated Telegraph Companies were celebrating their Jubilee, that 28 000 miles of submarine cable had been laid since the Armistice. When wireless telegraphy and telephony are making enormous strides to-day and there seems no limit to the possibilities of its further development, such figures as these seem to show that telegraphy by wires is more than holding its own against its younger rival.

While, then, telegraphy was a sturdy child at the date of the inception of the Institution and it was because of its growing and sturdy condition that the Institution, or as it was first and not unnaturally called, the Society of Telegraph Engineers, came into being—electric lighting, electric traction, electric power transmission, electric telephony and a whole long list of other now familiar electrical activities were non-existent. Radio communication, as Dr. Kennelly remarks, was then undreamt of.

In this shipbuilding "hub of the universe" a few facts regarding the genesis and progress of electric lighting and power transmission on board ship may be of interest to you, especially to those who, like myself, are engaged in this particular branch of our profession. Illumination by arc lamps was the first method adopted on board ship. This was only natural, seeing that the invention of the arc lamp preceded that of the Swan or incandescent lamp by several years. Then, too, the series connection of lamps was the only method thought to be possible at first. Parallel running, or "subdivision of the current" as it was then called, was hardly considered practicable, and it was apparently not until about the year 1880 that attempts were made in that direction. In that year Edison in America installed on the steamship "Columbia" 115 10-c.p. incandescent lamps and, apparently about the same time, arc lamps were used for the internal illumination of the steamship "City of Berlin." The following year (1881) saw, so far as I can learn, the first instance of incandescent electric lighting installed in a vessel built on the Clyde. This ship was the Cunard steamer "Servia," constructed by Messrs. G. and J. Thomson, Ltd., the founders of the Clydebank shipbuilding yard of to-day. This vessel had 117 Swan lamps and two arc lamps. The power required was about 10 kW and in all probability was furnished by a single-phase a.c. machine, driven by an endless cotton rope from a low-speed engine.

In this same year, incandescent electric lighting was introduced into the British Navy, the ship chosen being H.M.S. "Inflexible." Lord Fisher refers to the incident in the second volume of his memoirs and tells how it was owing to his interest in the Swan lamp and to Mr. Henry Edmund's lucid demonstration of it in a shed in Portsmouth Dockyard in the presence of the Admiral, surrounded by such a bevy of ladies as reminded Mr. Edmunds of his prototype in "H.M.S. Pinafore," with "his sisters and his cousins and his aunts," that the momentous decision was made to install this new illuminant in the "Inflexible," of which Fisher was then Captain.

Mr. James Lowson in his address to the Scottish Centre * mentioned the interesting fact that the first insulated wires used for ship lighting were covered with cotton cloth and white lead and that where they had to pass through specially damp places they were provided with additional protection of rubber tubing. Mr. J. H. Holmes, one of the pioneers of this branch of the industry, tells how they nearly set the "City of Rome" on fire after starting up the generating machinery. Seemingly they did not know much about fuses in those days and, to their consternation, sulphurous smoke was seen arising from the rubber-insulated wires in the music saloon. There being no switches nearer to hand than the engine room, a rush was made for it, the fire was extinguished and the painters bribed to work all night and cover up all traces of the mishap. Mr. Holmes's remarks about the absence of switches recalls to my mind a report made by one of my friends on the trials of the generating plant fitted on board the s.s. "Friesland," a steamer built in 1889, which it is interesting to find was, even at that early date, fitted with a Parsons turbo-generator.

He says: "One turbo-generator alone carried the full load of lights without the slightest hitch. The main cable was drawn out of its binding post repeatedly, thus throwing off the full load of 450 lamps, but the engine adjusted its speed instantaneously without the stop valve being touched at all." He says nothing about the replacing of the cable into its binding post. Presumably that also was done with the generator running, altogether rather a difficult business.

As you are all probably aware, the earliest form of incandescent lamp manufactured in this country was the carbon-filament type, invented by Sir Joseph Swan, I think, in the year 1878. They were far from being a satisfactory article at first, as they were made from parchmentized cotton and were very fragile. Breakages were numerous and, as the price was 35s. per lamp, experimenting with them was a decidedly costly affair. Glasgow has, we are told, the distinction of being the first town in this country in which this new form of illuminant, the Swan carbon-filament lamp, was publicly exhibited. The outcome of this exhibition was that Colonel Crompton got orders to install these lamps in the Glasgow Post Office and the goods yard of Queen-street station. The next step in lamp manufacture was the Nernst lamp, followed by the tantalum filament. From that we have come to the tungsten lamp and, last and perhaps the greatest jump in improvement of all, the gasfilled lamp. How tremendously we have progressed in the making of incandescent lamps since those pioneering days 40 years ago can only be fully appreciated after walking through a modern lamp factory and witnessing the hundred-and-one processes, some performed by hand labour and others by the most ingenious of automatic machinery, through which the vacuum and gasfilled lamps have to pass before they reach the final stage in their manufacture.

Reverting again for a few moments to the progress made in the application of electrical science to the navigation and internal economy of the modern steamship since those days, 40 years ago, when the electric lamp began to displace the evil-smelling and dangerous oil lamp, it is only natural that we should find electricity being first used as a transmitter of power for driving fans to improve the ventilation of the lower decks. Since then it has found ever-increasing application on board ship until practically every piece of rotating machinery outside of the engine room, and much of the auxiliary machinery within it as well, is now driven electrically. For every purpose requiring the transmission of orders, messages, records of movements of gearing of all kinds, temperature indications, the rejuvenation of the human frame by artificial solar heat and the still more artificial hobby horse, the ozonizing of vitiated atmosphere and many other purposes too numerous to mention here, electricity is becoming more and more indispensable in the modern passenger liner. Last winter one of your members gave an exhaustive description of the gyroscopic compass, an instrument which was made possible by the application of electric power, and which is threatening to displace the magnetic compass in our large liners, owing to its many advantages over its older rival.

Electricity has also made possible another application of the gyro wheel. I refer to what is known as the Sperry "stabilizer," by means of which it is possible to reduce the rolling of a vessel even in the worst of weather. Apart from the obvious comfort which such a device must bring to the average passenger who is prone to suffer from *mal de mer*, it has the less obvious commercial advantage of appreciably reducing the power required to propel a vessel in heavy weather and of greatly minimizing the shipping of seas by keeping it on an almost even keel. Of course I should mention that these applications of the gyroscope to the navigation of ships are costly, more particularly the stabilizer, and can be considered only where the shortening of the voyage by maintaining a straighter course and the saving in propulsive effort more than counterbalance the capital outlay.

The advantages of electric heating and cooking are beginning to be more and more appreciated on board ship and already we find the coal-fired cooking range being displaced by an electrically heated one on some of our cross-channel steamers. This is not surprising, for the benefits to be derived from electric cooking, which are so self-evident in the domestic kitchen, are even more apparent in the galleys of such vessels. The cleanliness, comfort and absence of waste heat require to be seen and experienced to be fully appreciated by those accustomed only to the older methods and discomforts of coal-fired ranges.

---

* *Journal I.E.E.*, 1915, vol. 53, p. 37.

The advent of the Diesel motor ship has given a fresh fillip to the electrical industry. A cargo steamer of possibly 10 000 tons' carrying capacity, which, if propelled by reciprocating steam engines or geared turbines, might have a small electric lighting plant of about 25 kW, will probably now have generators of a total capacity of 400 to 500 kW, the absence of steam boilers necessitating the whole of the deck machinery, including steering gear, capstans and windlasses and, in the engine room, large air compressors and all the pumping plant, ventilating fans and refrigerating machinery, being electrically driven.

From this point I might proceed to describe the position in which we stand to-day as regards electric propulsion of ships and some of the later uses to which electricity has been applied in their construction. I feel, however, that I could not do justice to such a theme in a few passing remarks and I propose, therefore, to turn instead to one or two topics which it seems to me are peculiarly of interest to Students of the Institution.

The first thing I should like to say to you is that it is far harder to rise in your profession to-day than it was in the early days of the industry. It was then, in comparison with to-day, relatively easy to rise above one's fellows and to become, shall I say, a giant among pygmies. Forty years ago the biggest intellects in the world were engaged in developing existing industries. The average electrician of those days was but a dabbler in science and an amateur in invention. Consequently it was comparatively easy to rise in the industry and to maintain one's reputation in the face of a gradually growing influx of younger trained men. To-day we have a very large number of highly trained scientific and business men engaged in the electrical profession. The problems which were then difficult and seemingly impossible of solution are now quite elementary and easily understood. The problems which remain to be solved are of a very much more abstruse character and are being tackled by many who have benefited by the discoveries of those early pioneers and whose equipment for such research work is infinitely superior to their predecessors'. It is for such reasons as this that I say that it is exceedingly difficult to-day for any but the most brilliant genius to rise much above the level of his competitors. I am not saying these things to discourage you but in order that you should appreciate how much greater is the necessity for continuous effort if you are to attain to eminence in your profession to-day.

Now, while it is not given to every one of you to rise in his profession much above the average level and thus to make your influence felt in the world, each may leave his mark upon his work in a manner which may be even more enduring than if he succeeded for a time in soaring above his fellows in public estimation. Every piece of work undertaken bears the impress of the worker, and the character of that impress depends upon the thoroughness with which it has been done and the spirit which has animated the doer. In the long run, the money-getting value of any piece of work is of the least importance. Of far greater value to the engineer and that which will advance him in the estimation of his fellow-men is the manner in which he has carried out his contract. Of course, every engineering problem involves questions of cost, and the successful engineer is he who employs the least capital in a job which in its working gives the greatest return on that capital outlay. This leads me on to say how very important it is that you young engineers should not lose sight of the commercial side of your professional training. Too little attention, I fear, has in the past been paid to this subject and, in consequence, many a student completes his college course or apprenticeship without realizing that the most important question that thereafter will confront him is the cost of the scheme which he is called upon to work out or the machine which he has to create.

It is not unnatural for the young engineer to lose sight of this fact. If he is at all keen on his work, what is more natural than that he should strive after perfection, but, in this imperfect world, perfection is a costly virtue and a luxury which can rarely be afforded. Then, too, the experience through which he has recently come during the years of war, when it was a case of getting everything done regardless of cost, has not helped to bring this fact home to him.

Some, if not indeed many, of you will have occasion to draw up specifications of work to be done. Here you have a subject of the very greatest importance to which I doubt if very much attention is paid in the training of the young engineer. Unless you are an expert in the manufacture of the machinery the performance of which you are specifying, and not even then, should you make the mistake of describing in detail how that machinery should be designed. That is not the object of a specification and, as I shall proceed to show you by one or two concrete examples, such a mistaken view of the nature of a specification often leads to waste of your own or your client's capital, with no counterbalancing advantage to you or to him. The main object of a specification is to state the duty which the machine or installation is intended to perform, the conditions under which it will operate, and the tests which will be applied in order to ascertain whether the performance is satisfactory. It is most essential if the cheapest, and at the same time the best, results are to be obtained, that the manufacturer or contractor should not be hidebound by stringent clauses in the specification, detailing how the desired results should be obtained. In such matters he should be left with the utmost freedom to adopt such methods of construction as he considers will reasonably fulfil the prescribed conditions. Of course the purchaser may have had previous experience with different kinds and qualities of material or methods of construction, and if such experience leads him to object to the employment of certain materials or methods of construction, he may quite properly specify that if such materials are utilized, they shall fulfil certain conditions as regards, for instance, their tensile strength and that certain methods of construction shall not be employed. It is then open to the manufacturer to offer such other materials or methods of construction as he can guarantee from his experience are best suited to the machinery manufactured by him. It is, for instance, much more important that the manufacturer should be informed that the machine sought for shall be capable of being operated in, say, an engine room having a temperature of 120° F. and in a damp tropical climate, than that the coils shall consist of copper wire having a conductivity not less than 98 per cent of Matthiessen's standard; also that the current density in the conductors shall not be more than 1 500 amperes per square inch in the armature coils and 2 000 amperes in the field coils, and so on. It is surely only common sense to expect that the manufacturer will, for his own protection, use copper of the highest conductivity, properly annealed, and designers of electrical machinery will tell you that the current density at which the windings may safely be run depends very largely upon the cooling conditions. In some cases, such as shunt coils, it may not be found practicable to go beyond 800 amperes per square inch, while in the construction of the armature, the ventilating and heat-radiating surfaces may allow of a density far above 1 500 amperes per square inch being employed with impunity and still meet the temperature, i.e. the essential, clause of the specification.

I have quite recently come across instances, in private and Government practice, where, owing to just such causes as I have mentioned, some too obviously the result of slavishly copying out-of-date specifications, others of seemingly ignorant attempts to improve upon sound practice by piling safeguards upon safeguards already existing, hundreds of pounds have, or will be, needlessly thrown away and presumably by well-intentioned individuals who unfortunately act for clients who are unaware of these facts. And so I would close this topic by again impressing upon all young engineers the fact that the object of a specification is mainly to ensure the attainment of results and not to teach the manufacturer his business. Inform him as to what your plant is to accomplish, tell him the conditions under which it will have to work, and, having placed your contract in the hands of a firm of repute, it will be sufficient for you to see that they meet their guarantees.

It would be foolish to attempt to foretell the future, even its immediate prospects, for it must be very humiliating at this time to those who told us less than three years ago that the conditions then existing would probably continue for many years to come and that in consequence the prospect of employment for educated and trained electrical engineers was very promising. The situation, I need hardly tell you, is far from rosy, and as regards unemployment and the immediate prospects of employment for the younger men, especially in the engineering professions, things could hardly be worse than they are just now, but history has in the past repeated itself and will surely repeat itself again. The lean and anxious times we are passing through will assuredly pass away sooner or later—I venture to think that we have seen the worst already—and while we must not expect, nor should we expect, the industrial world of the future to work under conditions precisely similar to those prevailing before the war, I feel certain that there will be ever-increasing opportunities for those of you who are preparing yourselves to take advantage of them.

There are many new fields for the use of electricity which we have only begun to develop in this country. The Chairman of our Scottish Centre, Mr. A. S. Hampton, in his address told us of what has been done and of what remains to be done in the electrification of railways. Dr. Magnus Maclean has opened our eyes to the potentialities of water power in the Highlands; while Mr. Borlase Matthews told us recently of the beginnings of, and prospects for, electro-farming or the application of electricity to agriculture which, when we think of it, is still the greatest and the most essential industry in the world. The electrical propulsion of ships has only just made a beginning—I shall not venture to prophesy or express an opinion as to its future development. Radio-telephony may, if properly handled and developed, bring about profound changes in our domestic and economic life.

The Institution exists to promote and encourage every new endeavour and every new development in electrical science, and it is worthily fulfilling these functions. I would, however, have you remember that the future lies in your hands. Some of you will doubtless become Members of Council, and those of you who do not, will at least be able to criticize those who do. Some of you may be inclined to criticize the Council already, and such criticism is to be welcomed if the critic has the welfare of the Institution genuinely at heart. When you criticize do not, however, forget that the responsibility of office carries with it the cares of office, and that, while all things may be lawful, all things may not be expedient. The Council are trustees for its 10 000 members and, as such, must not be expected to launch into speculative ventures which may turn out disastrously for the health of the Institution. In closing, let me say that by doing what within you lies to promote the welfare of this Students' Section, you will be helping the Institution to attain to an even greater reputation than it holds to-day.

# THE OPERATION OF INDUCTION MOTORS IN CASCADE.*

By H. COTTON, M.B.E., M.Sc., Associate Member.

(*Paper first received* 10*th April, and in final form* 4*th November,* 1922.)

The circle diagram of two induction motors in cascade can be drawn by elaborating the diagram for one machine functioning under normal conditions.

Let $F_1$ = useful primary flux, i.e. the primary flux which links with the secondary winding.
$f_1$ = primary leakage flux.

Then $(F_1 + f_1)$ = total primary flux $= \phi_1$, say, and $\phi_1 = \lambda_1 F_1$, where $\lambda_1$ is the primary leakage factor.

Let $F_2$ = useful secondary flux, i.e. the secondary flux which links with the primary winding.
$f_2$ = secondary leakage flux.

Then $(F_2 + f_2)$ = total secondary flux $= \phi_2$, say, and $\phi_2 = \lambda_2 F_2$, where $\lambda_2$ is the secondary leakage factor. Hence the resultant primary flux is the vector sum of $\phi_1$ and $F_2$, and the resultant secondary flux is the vector sum of $\phi_2$ and $F_1$. Remembering that the resultant secondary flux is in quadrature with the total flux produced by the secondary winding alone, i.e. with $\phi_2$, we can draw the diagram for a single motor as follows :—

Draw Oa (Fig. 1) to represent $F_1$, and on Oa as diameter describe a semicircle.

From a draw a chord aC to represent $\phi_2$ $(= F_2 + f_2)$. Join OC and draw OB parallel to aC, making $\mathrm{OB} = \mathrm{aC} = \phi_2$. Then, since angle COB is a right angle, and since OC is the resultant of Oa and OB,

OC = resultant secondary flux.

Produce Oa to A, making $\mathrm{OA} = F_1 + f_1 = \phi_1$. Mark off $\mathrm{Ob} = F_2$. Then OD the vector sum of $\phi_1$ and $F_2$ is the resultant primary flux.

In the case of a motor functioning alone, the line OD is the fixed line on the diagram, and its length is proportional to the magnetizing current. OA is proportional to the primary current on load, and the locus of A is a semicircle with its centre on OD produced.†

In order to derive the circle diagram of the cascade motor the following considerations have to be taken into account :—

First, the second motor being connected to the first motor receives its supply from this. The first motor is therefore functioning as a generator relative to the second. Also, in the case considered it is the rotor of the second machine which is the primary of that machine, and the stator which is acting as its short-circuited secondary. This latter condition is not, however, essential, as the stator of the auxiliary machine can be connected to the rotor of the main machine if the windings are designed with this end in view. The rotor-to-rotor method is treated here because it is suitable for two identical machines and therefore considerably simplifies the problem.

Secondly, because the rotor of the auxiliary machine is motoring on a current taken from the main rotor it will produce a back E.M.F. In order to simplify the diagram the case considered is that of ideal motors in which the copper losses are so small that they can be neglected. This means that the generated E.M.F. in the main rotor and the back E.M.F. in the auxiliary rotor will be equal and opposite. But the directions of rotation of the two rotors are the same, the shafts being mechanically coupled, hence the fluxes which produce these E.M.F.'s must be in phase with one another when drawn on the same diagram. Also, assuming identical windings on the two rotors, the two fluxes must be equal in magnitude. The flux diagram of the auxiliary machine is drawn first.

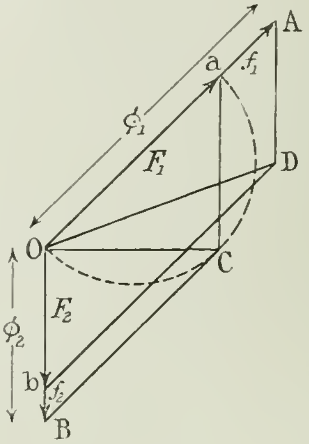


FIG. 1.

Let ${}_1F_1$ = useful primary flux of machine 1.
${}_1F_2$ = useful secondary flux of machine 1.
${}_2F_1$ = useful primary flux of machine 2.
${}_2F_2$ = useful secondary flux of machine 2.

And so on, the prefix referring to the number of the machine, and the suffix to the winding, e.g. whether primary or secondary.

Mark off $\mathrm{Oa} = {}_2F_1$ the useful primary flux (Fig. 2), and make $\mathrm{OA} = \lambda_2 {}_2F_1 = {}_2\phi_1$, the leakage factor $\lambda_2$ being used because the rotor is functioning as the primary and the stator as secondary.

On Oa as diameter describe a semicircle and mark off the chord aC equal to the total secondary flux ${}_2\phi_2$. Then the resultant OC = the resultant secondary (stator) flux. Also making Ob = OB/$\lambda_1$ we have for the resultant of OA and Ob, OD = the resultant primary (rotor) flux.

---

* This paper, which was submitted by the author as a thesis, was accepted by the Examinations Committee in lieu of the Associate Membership Examination.

† See BEHREND : "The Induction Motor."

Consider now the main motor. Since its rotor must have induced in it an E.M.F. equal and opposite to that in the second rotor, the resultant flux linking with it must be equal to the resultant flux of the second rotor, namely, to OD. One of the components of this resultant flux is the total flux produced by the rotor winding itself, that is OA = ${}_1\phi_2$ in the diagram, since the total rotor flux is the same in each machine. But since the rotor currents must be equal and opposite, the total rotor flux of machine 1, namely, ${}_1\phi_2$, must be opposite in phase to the vector OA and therefore represented on the diagram by OE, where OE = OA.

The other component of the resultant rotor flux is the useful stator flux ${}_1F_1$.

Producing OF to G and making OG equal to $\lambda_1$OF we have OG = ${}_1\phi_1 = \lambda_1 \cdot {}_1F_1$, the total primary (stator) flux of the main machine. Finally, since the resultant stator flux is the vector sum of the total stator flux ${}_1\phi_1$ and the useful rotor flux ${}_1F_2$, we can find this resultant flux as follows :—

OE represents the total rotor flux ${}_1\phi_2$. Hence, if we mark off OH equal to OE/$\lambda_2$, we have OH = ${}_1F_2$.

Completing the parallelogram OHKG gives OK the resultant primary flux. This completes the flux diagram.

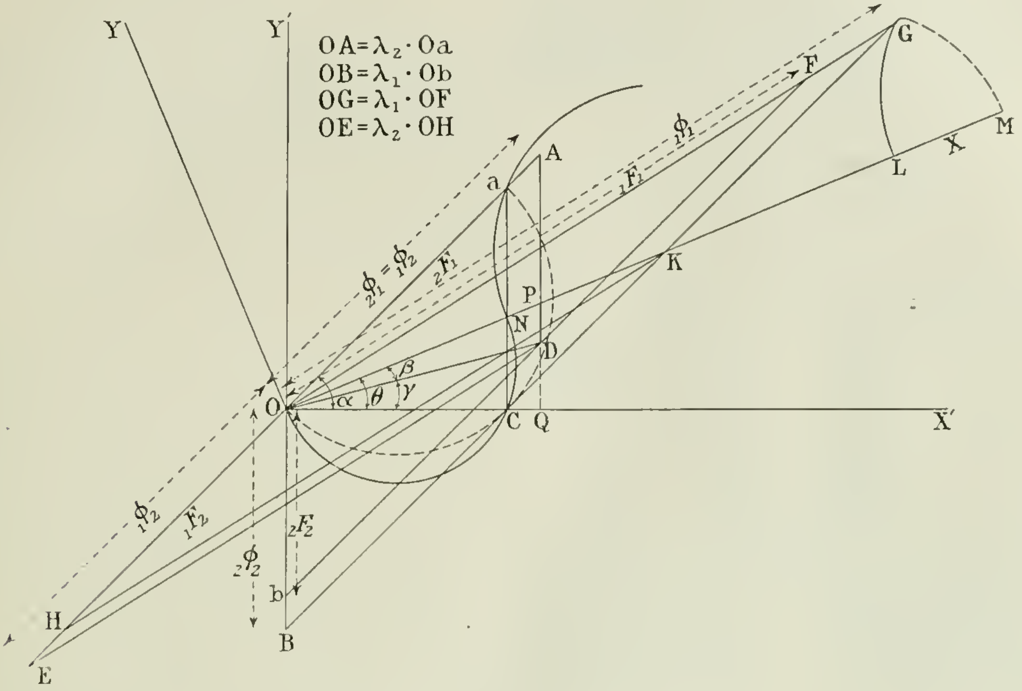


Fig. 2.—Construction of the circle diagram.

Since the currents are proportional to the fluxes which they set up, the flux diagram is also, to a certain scale, a current diagram. Hence the vector OG, which represents the total flux set up by the current in the primary motor, also represents the current intake of the whole set. Hence the locus of G is the required current diagram. The fixed line on the diagram is given by the vector OK representing the resultant primary flux. This line is constant in magnitude and direction, and is analogous to the fixed line OD in the circle diagram for a single motor. OK gives, when measured on the current scale, the magnetizing current of the set. Fig. 3 shows the completed diagram.

The locus of G is determined analytically as follows :—

Take the direction of OC as the $x'$ axis, and the perpendicular through O as the $y'$ axis. Then the co-ordinates of the various points on the diagram are as follows :—

$x'$ co-ordinate of C = ${}_2F_1 \cos \alpha$ : $y'$ co-ordinate = 0
$x'$ co-ordinate of $a$ = ${}_2F_1 \cos \alpha$ : $y'$ co-ordinate = ${}_2F_1 \sin \alpha$
$= {}_2\phi_2$
$= \lambda_1 \cdot {}_2F_2$

$x'$ co-ordinate of
$A = \lambda_2\, {}_2F_1 \cos \alpha$ : $y'$ co-ordinate = $\lambda_2\, {}_2F_1 \sin \alpha$
$= \lambda_1\lambda_2 \cdot {}_2F_2$

OD is the resultant of OA and Ob. Hence

$x'$ co-ordinate of D = $\lambda_2 \cdot {}_2F_1 \cos \alpha$ : $y'$ co-ordinate
$= \lambda_1\lambda_2 \cdot {}_2F_2 - {}_2F_2$

OF is the resultant of OA and OD. Therefore

$x'$ co-ordinate of F = $2\lambda_2 \cdot {}_2F_1 \cos \alpha$ : $y'$ co-ordinate
$= 2\lambda_1\lambda_2 \cdot {}_2F_2 - {}_2F_2$

OG is $\lambda_1$ times OF, hence its $x'$ and $y'$ co-ordinates are $\lambda_1$ times the corresponding co-ordinates of OF. Therefore

$x'$ co-ordinate of $G = 2\lambda_1\lambda_2 \cdot {}_2F_1 \cos \alpha$ : $y'$ co-ordinate of
$G = \lambda_1 \cdot {}_2F_2(2\lambda_1\lambda_2 - 1)$

Finally, GK is equal and parallel to OH $= {}_1F_2 = {}_2F_1$ reversed. Therefore

$$
\begin{aligned}
x' \text{ co-ordinate of } K &= 2\lambda_1\lambda_2 \,.\, {}_2F_1 \cos a - {}_2F_1 \cos a \\
&= {}_2F_1 \cos a (2\lambda_1\lambda_2 - 1) \\
y' \text{ co-ordinate of } K &= \lambda_1 \, {}_2F_2(2\lambda_1\lambda_2 - 1) - {}_2F_1 \sin a \\
&= \lambda_1 \, {}_2F_2(2\lambda_1\lambda_2 - 1) - \lambda_1 \, {}_2F_2 \\
&= 2\lambda_1 \, {}_2F_2(\lambda_1\lambda_2 - 1)
\end{aligned}
$$

Now since the only fixed direction on the diagram is the direction of OK, it is desirable to use OK as the $x$ axis, and the perpendicular through O as the $y$ axis. The new axes are therefore displaced by an angle KOC ($= \theta$, say) from the old axes in a counter-clockwise direction. Hence the equations for transformation are:

$$
\left.\begin{aligned}
x &= x' \cos\theta + y' \sin\theta \\
y &= y' \cos\theta - x' \sin\theta
\end{aligned}\right\}
$$

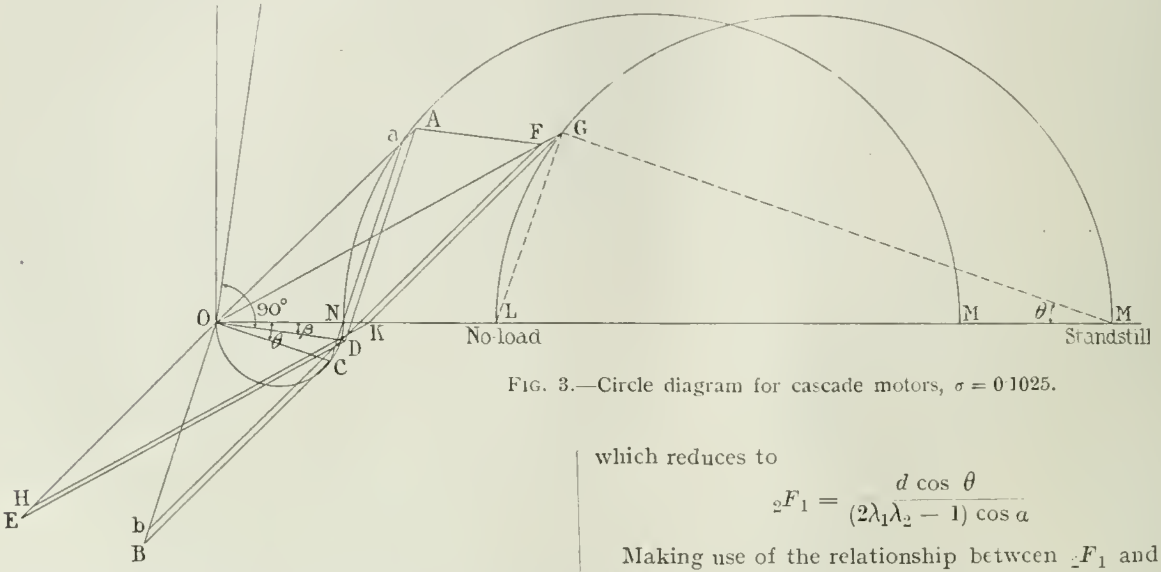


FIG. 3.—Circle diagram for cascade motors, $\sigma = 0{\cdot}1025$.

Hence for the co-ordinates of K (a fixed point) with respect to the new axes we have:

The $x$ co-ordinate

$$
\begin{aligned}
&{}_2F_1 \cos a \cos\theta(2\lambda_1\lambda_2 - 1) \\
&\qquad + 2\lambda_1 \,.\, {}_2F_2 \sin\theta(\lambda_1\lambda_2 - 1) = d, \text{ say} \quad . \quad (1)
\end{aligned}
$$

The $y$ co-ordinate

$$
\begin{aligned}
&- {}_2F_1 \cos a \sin\theta(2\lambda_1\lambda_2 - 1) \\
&\qquad + 2\lambda_1 \,.\, {}_2F_2 \cos\theta(\lambda_1\lambda_2 - 1) = 0 \quad . \quad (2)
\end{aligned}
$$

From Equation (2) we can deduce a relationship between $a$ and $\theta$, for we have

$$
{}_2F_1 \cos a \sin\theta\,(2\lambda_1\lambda_2 - 1) = 2\lambda_1 \,.\, {}_2F_2 \cos\theta\,(\lambda_1\lambda_2 - 1)
$$

Again,
$$
\begin{aligned}
\lambda_1 \,.\, {}_2F_2 &= {}_2\phi_2 \\
&= {}_2F_1 \sin a
\end{aligned}
$$

Hence substituting in the above equation we have

$$
\cos a \sin\theta\,(2\lambda_1\lambda_2 - 1) = 2 \sin a \cos\theta\,(\lambda_1\lambda_2 - 1) \quad . \quad (3)
$$

The co-ordinates of G with respect to the new axes are:

$$
\begin{aligned}
x &= d + \text{GK} \cos(a - \theta) \\
&= d + {}_2F_1 \cos(a - \theta) \\
y &= \text{GK} \sin(a - \theta) \\
&= {}_2F_1 \sin(a - \theta)
\end{aligned}
$$

Again, from Equations (1) and (2) we can determine the relationship between ${}_2F_1$, ${}_2F_2$ and $d$; for from Equation (2) we have

$$
{}_2F_2 = \frac{{}_2F_1 \cos a \sin\theta(2\lambda_1\lambda_2 - 1)}{2\lambda_1 \cos\theta(\lambda_1\lambda_2 - 1)}
$$

Substituting this value in Equation (1) we have

$$
\begin{aligned}
&{}_2F_1 \cos a \sin\theta\,(2\lambda_1\lambda_2 - 1) \\
&\quad + \frac{2\lambda_1 \sin\theta(\lambda_1\lambda_2 - 1) \times {}_2F_1 \cos a \sin a(2\lambda_1\lambda_2 - 1)}{2\lambda_1 \cos\theta(\lambda_1\lambda_2 - 1)} = d
\end{aligned}
$$

which reduces to

$$
{}_2F_1 = \frac{d \cos\theta}{(2\lambda_1\lambda_2 - 1)\cos a}
$$

Making use of the relationship between ${}_2F_1$ and ${}_2F_2$ we have

$$
{}_2F_2 = \frac{d \sin\theta}{2\lambda_1(\lambda_1\lambda_2 - 1)}
$$

Hence the $y$ co-ordinate of G becomes

$$
\begin{aligned}
y &= {}_2F_1(\sin a \cos\theta - \cos a \sin\theta) \\
&= {}_2F_1\left\{\sin a \cos\theta - \frac{\sin a \cos\theta \times 2(\lambda_1\lambda_2 - 1)}{2\lambda_1\lambda_2 - 1}\right\}
\end{aligned}
$$

from Equation (3)

Again,
$$
\begin{aligned}
{}_2F_1 &= \frac{\lambda_1 \, {}_2F_2}{\sin a} \\
&= \frac{d \sin\theta}{2(\lambda_1\lambda_2 - 1)\sin a}
\end{aligned}
$$

Hence the expression for $y$ reduces to

$$
y = \frac{d \sin\theta \cos\theta}{2(\lambda_1\lambda_2 - 1)\,(2\lambda_1\lambda_2 - 1)} \quad . \quad . \quad . \quad (4)
$$

In order to simplify calculation, transfer the origin temporarily to K. Then the new $x$ co-ordinate of point G becomes

$$x = {}_2F_1 \cos(\alpha - \theta)$$
$$= \frac{d \sin\theta}{2(\lambda_1\lambda_2 - 1)\sin\alpha} \times \left\{\cos\alpha\cos\theta + \sin\alpha\sin\theta\right\}$$

Substituting

$$\cos\alpha\sin\theta = \frac{\cos\theta\sin\alpha \times 2(\lambda_1\lambda_2 - 1)}{2\lambda_1\lambda_2 - 1}$$

we have

$$x = \frac{d}{2(\lambda_1\lambda_2 - 1)\sin\alpha} \times \left\{\frac{\cos^2\theta\sin\alpha \times 2(\lambda_1\lambda_2 - 1)}{2\lambda_1\lambda_2 - 1} + \sin\alpha\sin^2\theta\right\}$$
$$= \frac{d}{2(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \times \left\{2\lambda_1\lambda_2 - 1 - \cos^2\theta\right\} \quad (5)$$

In order to find an equation connecting $x$ and $y$ we have to eliminate the functions of $\theta$. Expressing in terms of $2\theta$ we have

$$y = \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\sin 2\theta$$
$$x = \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\left\{4\lambda_1\lambda_2 - 2 - (1 + \cos 2\theta)\right\}$$
$$= \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}(4\lambda_1\lambda_2 - \cos 2\theta - 3)$$

Put $$\frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} = P$$

Then $$y = P\sin 2\theta$$
$$x = P(4\lambda_1\lambda_2 - 3 - \cos 2\theta)$$

Put $$(4\lambda_1\lambda_2 - 3) = Q$$

Therefore $$x = P(Q - \cos 2\theta)$$

Hence squaring and adding we have

$$x^2 + y^2 - P^2(Q^2 - 2Q\cos 2\theta) = P^2$$

Again, $$-\cos 2\theta = \left(\frac{x}{P} - Q\right)$$

Therefore $$x^2 + y^2 - P^2\left(Q^2 + \frac{2Qx}{P} - 2Q^2\right) = P^2$$

Therefore $$y^2 + (x - PQ)^2 = P^2$$

Re-substituting for $P$ and $Q$ we have

$$y^2 + \left\{x - \frac{4(\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\right\}^2 = \left\{\frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\right\}^2$$

This is the equation to a circle of radius

$$c = \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}$$

with its centre on the $x$ axis situated at a distance

$$a = \frac{(4\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \text{ from K}$$

It is usual to express the quantities $c$ and $a$ in terms of the "dispersion coefficient" of the motor. This is sometimes taken as

$$\sigma = \lambda_1\lambda_2 - 1 \text{ and sometimes as } \sigma = 1 - \frac{1}{\lambda_1\lambda_2}$$

Taking the first as the more commonly used value we have

$$\lambda_1\lambda_2 = \sigma + 1$$

Hence the radius $$c = \frac{d}{4\sigma(2\sigma + 1)}$$

Retaining K as the origin, the points L and M, where the circle cuts the $x$ axis, are given by the condition $y = 0$. Therefore

$$x - \frac{(4\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} = \pm\frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}$$
$$x = \frac{d}{4(\lambda_1\lambda_2 - 1).(2\lambda_1\lambda_2 - 1)}\left\{4\lambda_1\lambda_2 - 3 \pm 1\right\}$$
$$= \frac{d(4\lambda_1\lambda_2 - 2)}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \text{ or } \frac{d(4\lambda_1\lambda_2 - 4)}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}$$

This gives $$\text{KL} = \frac{d \times 4\sigma}{4\sigma(2\sigma + 1)}$$
$$= \frac{d}{2\sigma + 1}$$
$$\text{KM} = \frac{d(4\sigma + 2)}{4\sigma(2\sigma + 1)}$$

Now the distances of points on the circle from the original origin O are proportional to the fluxes or to the currents. Thus the length OL measured on the current scale gives the no-load current, that is the magnetizing current of the set. The length OM gives the standstill current.

We have $$\text{OM} = d + \frac{d(4\sigma + 2)}{4\sigma(2\sigma + 1)}$$
$$= \frac{d(8\sigma^2 + 8\sigma + 2)}{4\sigma(2\sigma + 1)}$$
$$= \frac{d(4\sigma + 2)}{4\sigma}$$
$$\text{OL} = d + \frac{d}{2\sigma + 1}$$
$$= \frac{d(2\sigma + 2)}{2\sigma + 1}$$

If we draw on the same diagram the circle for a single motor working alone, we can obtain a comparison between the two cases. The vector OG gives the total stator flux and OH the total rotor flux of the first machine. The resultant stator flux is OK, and therefore when measured on the stator current scale this length gives the no-load (magnetizing) current of one motor working alone. The phase will not be the same as that of OK, but this does not affect the numerical relationships between torque, power factor, etc., in the two cases.

Hence $\dfrac{\text{No-load current of combination}}{\text{No-load current of a single motor}} = \dfrac{OL}{OK}$

$$= \frac{d(2\sigma + 2)}{2\sigma + 1} \div d$$

$$= \frac{2\sigma + 2}{2\sigma + 1}$$

Now $\sigma = \lambda_1\lambda_2 - 1$

and therefore, since the leakage coefficients $\lambda_1$ and $\lambda_2$ have in practice to be very nearly equal to unity in order to keep the power factor as high as possible, the numerical value of $\sigma$ is very small when compared with unity. Hence the ratio of the magnetizing currents is very approximately two to one. This is to be expected since all the power received by the auxiliary motor has to come through the main motor, and the magnetizing current of the former is therefore superposed on that of the latter.

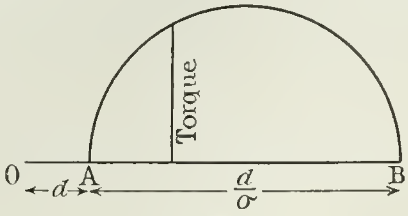


FIG. 4.

Again, for a single motor the ratio of the no-load current OA to the diameter of the circle AB is equal to the dispersion coefficient $\sigma$ (Fig. 4). Hence the diameter of circle for a single motor $= \dfrac{d}{\sigma}$. But the torque of the motor is proportional to the perpendicular dropped from the working point to the $x$ axis. Hence the maximum torque is proportional to the radius. Hence we have

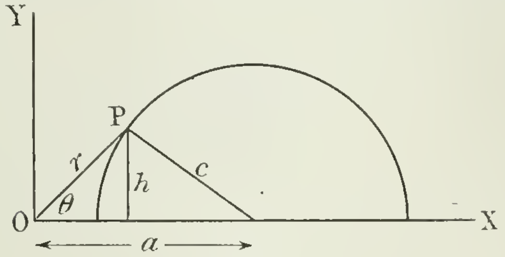


FIG. 5.

Maximum torque of main cascade motor is proportional to $c$, that is to $\dfrac{d}{4\sigma(2\sigma + 1)}$.

Maximum torque for a single motor working alone is proportional to $\dfrac{d}{2\sigma}$.

Hence

$$\frac{\text{Maximum torque of main cascade motor}}{\text{Maximum torque of single motor}} = \frac{1}{2(2\sigma + 1)}$$

$$= \tfrac{1}{2} \text{ (very nearly).}$$

The power factor (P.F.) for any working point P is given by the cosine of the angle POY, that is by the sine of the angle $\theta$ in Fig. 5 ($\theta$ now having a different meaning).

Therefore $\text{P.F.} = \dfrac{y}{\sqrt{(x^2 + y^2)}}$

But
$$y^2 + (x - a)^2 = c^2$$
$$y^2 + x^2 - 2ax + a^2 = c^2$$
$$x^2 + y^2 = c^2 + 2ax - a^2$$

and $y = \sqrt{[(c^2 - (x - a)^2]}$

Hence $\text{P.F.} = \sqrt{\left[\dfrac{c^2 - (x - a)^2}{c^2 + 2ax - a^2}\right]} = k$, say.

Differentiating with respect to $x$ we have

$$\frac{dk}{dx} = \tfrac{1}{2}\sqrt{\left[\frac{c^2 + 2ax - a^2}{c^2 - (x - a)^2}\right]} \times \frac{(c^2+2ax-a^2)[-2(x-a)]-\left\{c^2-(x-a)^2\right\}2a}{(c^2 + 2ax - a^2)^2}$$

This reduces to

$$\frac{dk}{dx} = \frac{-x\,(c^2 + ax - a^2)}{[c^2 - (x - a)^2]^{1/2} \times (c^2 - 2ax - a^2)^{3/2}}$$

This is equal to zero, and $k$ is a maximum when

$$c^2 + ax - a^2 = 0$$

i.e. $x = (a^2 - c^2)/a$

Hence the maximum power factor

$$= \frac{\sqrt{\left[c^2 - \left(\dfrac{a^2 - c^2 - a^2}{a}\right)^2\right]}}{\sqrt{[c^2 + 2(a^2 - c^2) - a^2]}} = \frac{c}{a}$$

Hence for the cascade set we have for the maximum power factor

$$\frac{d}{4\sigma\,(2\sigma + 1)} \div \left\{d + \frac{(4\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)\,(2\lambda_1\lambda_2 - 1)}\right\}$$
$$= \frac{1}{8\sigma^2 + 8\sigma + 1}$$

For a single motor we have the maximum power factor equal to

$$\frac{d}{2\sigma} \div \left(d + \frac{d}{2\sigma}\right) = \frac{1}{2\sigma + 1}$$

Hence

$$\frac{\text{Max. power factor of the set}}{\text{Max. power factor of single motor}} = \frac{2\sigma + 1}{8\sigma^2 + 8\sigma + 1}$$

The value of this ratio depends entirely upon the value of the dispersion coefficient. Hobart* gives a table showing the values of $\sigma$ for a large number of motors. For medium-sized and large machines it varies between 0·022 and 0·176. The above ratios for these values of $\sigma$ are 0·885 and 0·557. This shows the great objection to the cascade method of speed control, and the necessity of very careful design of the magnetic circuits if this system is to be adopted.

---

* "Electric Motors," 2nd ed., p. 478.

Comparisons of torque and power factor for any value of the intake are best shown by plotting these two quantities against a current base.

Expressed in polar co-ordinates we have, from Fig. 5,

$$\text{power factor} = \sin\theta$$
$$\text{current} = r$$
$$c^2 = a^2 + r^2 - 2ar\cos\theta$$
$$\cos\theta = \frac{a^2 + r^2 - c^2}{2ar}$$
$$\sin\theta = \sqrt{\left[1 - \left(\frac{a^2 + r^2 - c^2}{2ar}\right)^2\right]}$$

quantity $d$, namely, the magnetizing current of a single motor, we have

$$c_1 = \frac{d}{4\sigma(2\sigma + 1)}$$
$$a_1 = d + \frac{(4\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} = \frac{d(8\sigma^2 + 8\sigma + 1)}{4\sigma(2\sigma + 1)}$$
$$c_2 = \frac{d}{2\sigma}; \quad a_2 = \frac{d(2\sigma + 1)}{2\sigma}$$

Also the range of $r$ for a single motor will be from $d$ to $(d + d/\sigma)$, that is from $d$ to $d(1 + \sigma)/\sigma$.

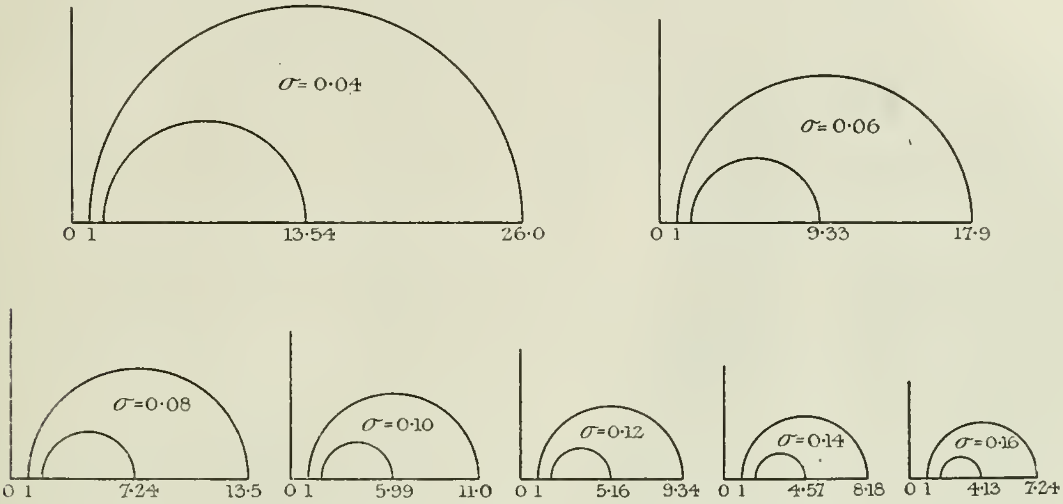


FIG. 6.—Circle diagrams for single induction motors and for two equal motors in cascade.
Outer circle—single motor. Inner circle—cascade motor.

Calling the values of $c$ and $a$, $c_1$ and $a_1$ for the cascade set, and $c_2$ and $a_2$ for a single motor we have

Power factor of cascade set

$$K_1 = \sqrt{\left[1 - \left(\frac{a_1^2 + r^2 - c_1^2}{2a_1 r}\right)^2\right]}$$
$$= \frac{\sqrt{(2a_1^2r^2 + 2a_1^2c_1^2 + 2c_1^2r^2 - a_1^4 - r^4 - c_1^4)}}{2a_1 r}$$

Torque of cascade set

$$T_1 = h_1 = r\sin\theta = r \times K_1$$
$$= \frac{\sqrt{(2a_1^2r^2 + 2a_1^2c_1^2 + 2c_1^2r^2 - a_1^4 - r^4 - c_1^4)}}{2a_1}$$

in arbitrary units.

Similarly for the single motor we have

Power factor

$$K_2 = \frac{\sqrt{(2a_2^2r^2 + 2a_2^2c_2^2 + 2c_2^2r^2 - a_2^4 - r^4 - c_2^4)}}{2a_2 r}$$

$$\text{Torque } T_2 = \frac{\sqrt{(2a_2^2r^2 + 2a_2^2c_2^2 + 2c_2^2r^2 - a_2^4 - r^4 - c_2^4)}}{2a_2}$$

in arbitrary units.

Expressing $c_1$, $a_1$, $c_2$ and $a_2$ in terms of the fixed

Practically all actual cases will be covered by taking values of $\sigma$ from 0·04 to 0·16, say the following values:

0·04, 0·06, 0·08, 0·10, 0·12, 0·14 and 0·16

The corresponding values of $c_1$, $a_1$, $c_2$ and $a_2$ are given in Table 1.

In the same table the standstill currents of a single motor and of the cascade set are given. The ratio of these currents is approximately 2 : 1 in all cases. The relative sizes of the circles are clearly shown in Fig. 6, which is drawn to scale.

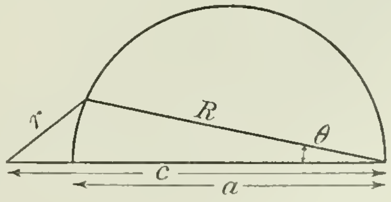


FIG. 7.

In Table 2 the torques, power factors and ratios of the torques and power factors are worked out for each value of $\sigma$ and plotted against a current base in

Figs. 8 to 11. Fig. 8 shows the torque $T_1$ of a cascade set in arbitrary units, while Fig. 9 gives the torque $T_2$ of a single motor. The inferiority of the cascade set is at once evident from a comparison of these curves.

TABLE 1.

*The Unit in which the Quantities $c_1$, $a_1$ and Standstill Current are expressed is the Magnetizing Current of a Single Motor.*

| $\sigma$ | Cascade motors | | | Single motor | | |
|---|---|---|---|---|---|---|
| | $c_1$ | $a_1$ | Current at standstill | $c_2$ | $a_2$ | Current at standstill |
| 0·04 | 5·8 | 7·74 | 13·54 | 12·5 | 13·5 | 26·0 |
| 0·06 | 3·72 | 5·61 | 9·33 | 8·45 | 9·45 | 17·9 |
| 0·08 | 2·69 | 4·55 | 7·24 | 6·25 | 7·25 | 13·5 |
| 0·10 | 2·08 | 3·91 | 5·99 | 5·0 | 6·0 | 11·0 |
| 0·12 | 1·68 | 3·48 | 5·16 | 4·17 | 5·17 | 9·34 |
| 0·14 | 1·395 | 3·17 | 4·57 | 3·59 | 4·59 | 8·18 |
| 0·16 | 1·185 | 2·945 | 4·13 | 3·12 | 4·12 | 7·24 |

For currents up to the standstill current of the cascade set the torque of a single motor follows almost a linear law, the droop of the curves being exceedingly small. On the other hand, the curves for the cascade motors droop very quickly, especially those having a high dispersion coefficient.

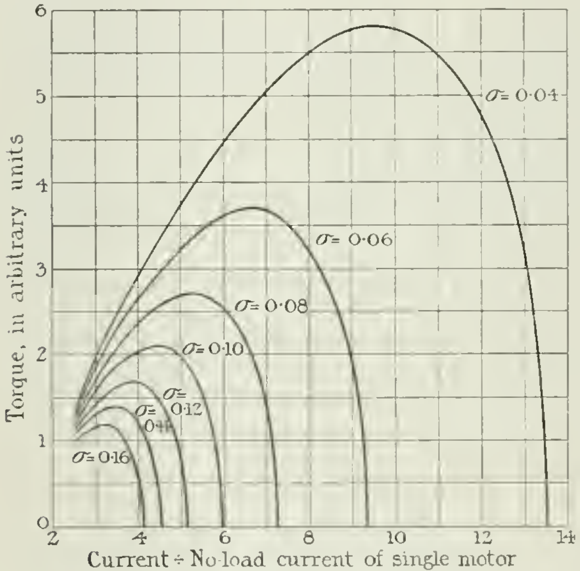


FIG. 8.—Curves showing torque of cascade motors.

Fig. 10 gives the power factors $K_1$ and $K_2$; here again the inferiority of the cascade motor is apparent, the maximum possible power factor being only 0·75 when the leakage is so small that $\sigma = 0 \cdot 04$.

Fig. 11 gives the ratios $T_1/T_2$ $(= K_1/K_2)$.

The study of these curves indicates, perhaps even more emphatically than has already been proved by other investigations, that if induction motors are to be operated in cascade with any success their magnetic circuits must be very carefully designed and every form of leakage reduced to an absolute minimum.

To complete the circle diagram it is necessary to include the circle giving the secondary current of the auxiliary motor. This is worked out as follows:—

Primary current in auxiliary motor
= secondary current in main motor
= GK

Secondary current in auxiliary motor = aC

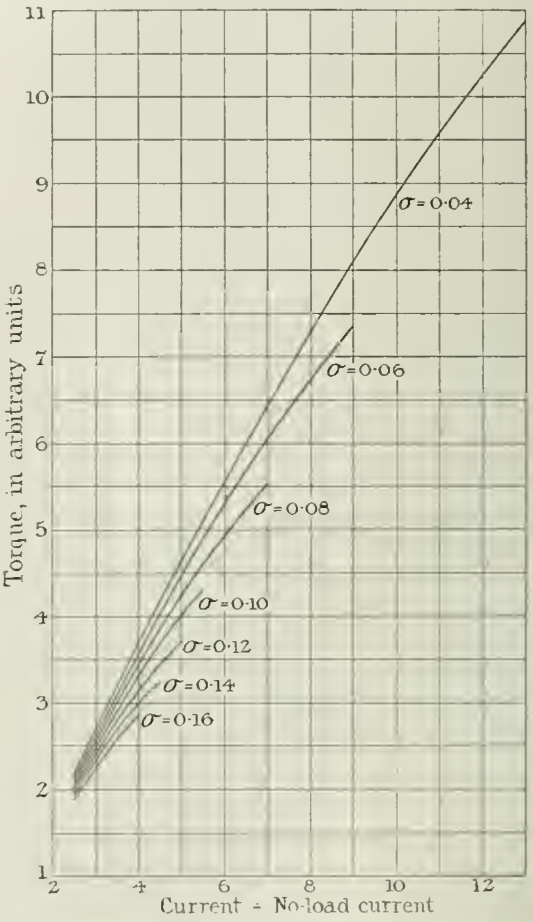


FIG. 9.—Curves showing torque of single motor.

Referred to $x'y'$ axes we have:

$x'$ co-ordinate of point $a = {}_2F_1 \cos \alpha$
$y'$ co-ordinate of point $a = \lambda_1 \, {}_2F_2$

Transforming to $xy$ axes we have, from

$$x = x' \cos \theta + y' \sin \theta \text{ and } y = y' \cos \theta - x' \sin \theta,$$
$$x = {}_2F_1 \cos \alpha \cos \theta + \lambda_1 \, {}_2F_2 \sin \theta$$
$$y = - {}_2F_1 \cos \alpha \sin \theta + \lambda_1 \, {}_2F_2 \cos \theta$$

Now
$$ {}_2F_1 = \frac{d \cos \theta}{(2\lambda_1\lambda_2 - 1) \cos \alpha}$$

and
$$ {}_2F_2 = \frac{d \sin \theta}{2\lambda_1(\lambda_1\lambda_2 - 1)}.$$

TABLE 2.

| Current $r$ | $T_1$ | $K_1$ | $T_2$ | $K_2$ | $\frac{T_1}{T_2} = \frac{K_1}{K_2}$ |
|---|---|---|---|---|---|
| $\sigma = 0·04$ | | | | | |
| 2·5 | 1·33 | 0·532 | 2·18 | 0·872 | 0·61 |
| 3 | 1·95 | 0·65 | 2·695 | 0·90 | 0·722 |
| 4 | 2·92 | 0·73 | 3·684 | 0·921 | 0·792 |
| 5 | 3·75 | 0·75 | 4·630 | 0·926 | 0·82 |
| 6 | 4·464 | 0·744 | 5·52 | 0·92 | 0·808 |
| 7 | 5·033 | 0·719 | 6·405 | 0·915 | 0·785 |
| 8 | 5·456 | 0·682 | 7·24 | 0·905 | 0·755 |
| 9 | 5·742 | 0·638 | 8·08 | 0·898 | 0·709 |
| 10 | 5·78 | 0·578 | 8·85 | 0·885 | 0·653 |
| 11 | 5·50 | 0·50 | 9·57 | 0·87 | 0·574 |
| 12 | 4·80 | 0·40 | 10·224 | 0·852 | 0·469 |
| 13 | 3·19 | 0·245 | 10·85 | 0·835 | 0·293 |
| $\sigma = 0·06$ | | | | | |
| 2·5 | 1·26 | 0·504 | 2·14 | 0·856 | 0·59 |
| 3 | 1·85 | 0·62 | 2·63 | 0·877 | 0·702 |
| 4 | 2·63 | 0·658 | 3·57 | 0·892 | 0·739 |
| 5 | 3·24 | 0·648 | 4·45 | 0·89 | 0·728 |
| 6 | 3·61 | 0·602 | 5·28 | 0·88 | 0·686 |
| 7 | 3·70 | 0·529 | 6·07 | 0·867 | 0·61 |
| 8 | 3·30 | 0·413 | 6·72 | 0·840 | 0·49 |
| 9 | 2·00 | 0·222 | 7·33 | 0·814 | 0·272 |
| $\sigma = 0·08$ | | | | | |
| 2·5 | 1·22 | 0·488 | 2·10 | 0·840 | 0·58 |
| 3 | 1·68 | 0·560 | 2·56 | 0·853 | 0·655 |
| 4 | 2·35 | 0·589 | 3·45 | 0·862 | 0·680 |
| 5 | 2·67 | 0·534 | 4·24 | 0·848 | 0·63 |
| 6 | 2·54 | 0·423 | 4·92 | 0·820 | 0·516 |
| 7 | 1·34 | 0·191 | 5·51 | 0·787 | 0·243 |
| $\sigma = 0·10$ | | | | | |
| 2·5 | 1·19 | 0·476 | 2·07 | 0·828 | 0·573 |
| 3 | 1·57 | 0·523 | 2·49 | 0·830 | 0·631 |
| 4 | 2·03 | 0·508 | 3·31 | 0·828 | 0·613 |
| 5 | 1·98 | 0·396 | 4·0 | 0·800 | 0·495 |
| 5·5 | 1·58 | 0·287 | 4·31 | 0·785 | 0·366 |
| $\sigma = 0·12$ | | | | | |
| 2·5 | 1·13 | 0·452 | 2·0 | 0·800 | 0·565 |
| 3·0 | 1·45 | 0·483 | 2·42 | 0·807 | 0·600 |
| 3·5 | 1·63 | 0·465 | 2·80 | 0·800 | 0·581 |
| 4·0 | 1·68 | 0·42 | 3·16 | 0·790 | 0·531 |
| 4·5 | 1·49 | 0·331 | 3·47 | 0·772 | 0·429 |
| 5·0 | 0·83 | 0·166 | 3·72 | 0·744 | 0·223 |
| $\sigma = 0·14$ | | | | | |
| 2·5 | 1·07 | 0·428 | 1·95 | 0·780 | 0·559 |
| 3·0 | 1·31 | 0·437 | 2·35 | 0·783 | 0·558 |
| 3·5 | 1·4 | 0·399 | 2·7 | 0·771 | 0·519 |
| 4·0 | 1·23 | 0·308 | 3·01 | 0·753 | 0·408 |
| 4·5 | 0·45 | 0·100 | 3·26 | 0·725 | 0·138 |
| $\sigma = 0·16$ | | | | | |
| 2·5 | 0·99 | 0·396 | 1·88 | 0·752 | 0·527 |
| 3·0 | 1·16 | 0·387 | 2·26 | 0·753 | 0·511 |
| 3·5 | 1·12 | 0·320 | 2·58 | 0·737 | 0·435 |
| 4·0 | 0·61 | 0·152 | 2·84 | 0·710 | 0·215 |

Hence
$$x = \frac{d\cos^2\theta}{(2\lambda_1\lambda_2 - 1)} + \frac{d\sin^2\theta}{2(\lambda_1\lambda_2 - 1)}$$
$$= \frac{d}{2(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\left\{2\lambda_1\lambda_2 - 1 - \cos^2\theta\right\}$$
$$= P(4\lambda_1\lambda_2 - 3 - \cos 2\theta)$$
= $x$ co-ordinate of point G referred to K as origin

Also
$$y = \frac{d\cos\theta\sin\theta}{2(\lambda_1\lambda_2 - 1)} - \frac{d\cos\theta\sin\theta}{(2\lambda_1\lambda_2 - 1)}$$
$$= \frac{d\cos\theta\sin\theta}{2(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}$$
$$= P\sin 2\theta$$
= $y$ co-ordinate of point G.

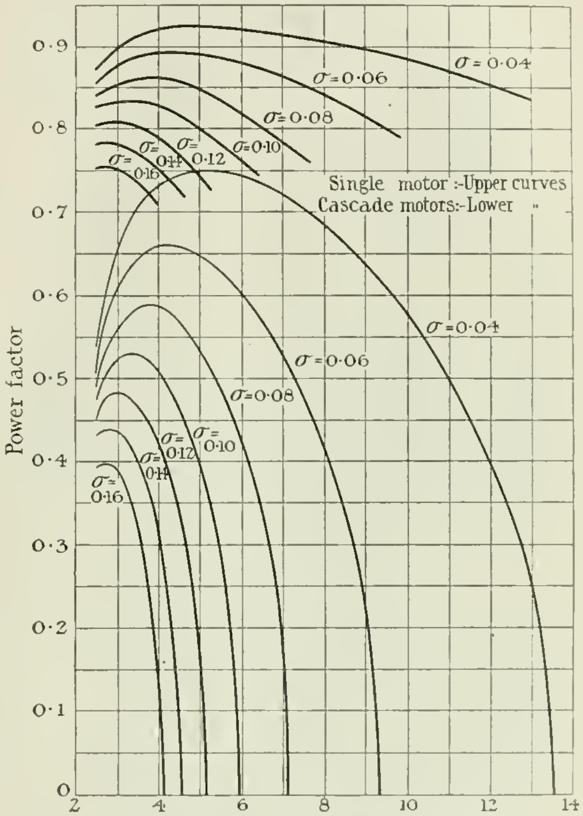


FIG. 10.—Power factor curves.

Hence the vector Oa is always equal and parallel to the vector GK, and points O and G are always located on the $x$ axis.

Again, the locus of G is the current circle of the main motor, hence the locus of "a," i.e. the extremity of the secondary current vector of the auxiliary motor, is a circle with radius equal to that of the main motor circle, and with its centre located on the $x$ axis distant

KL + radius of main motor circle
$$= \frac{4(\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \text{ from the origin.}$$

This circle cuts the $x$ axis at N, where ON = KL.

Now the torque of the main motor is given by the length of the perpendicular dropped from the working point on the stator current circle. Hence the torque of the auxiliary motor will be given by the length of the perpendicular dropped from the working point on the circle representing its own stator current. But these two circles have been proved to be identical (except that the centre of one is displaced along the $x$ axis relatively to the other). Hence the two perpendiculars will be equal, and therefore the torque developed by the auxiliary motor is equal to that of the main motor.

Next consider the locus of the point C, the other extremity of the secondary current vector of the auxiliary motor.

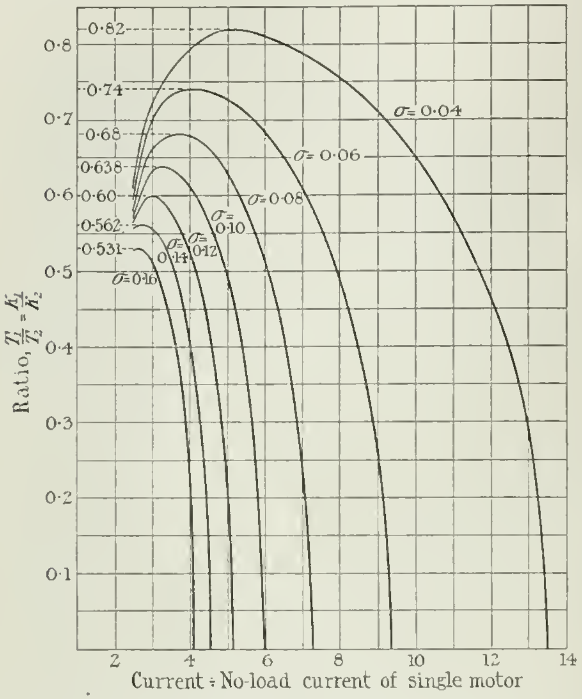


FIG. 11.—Curves showing the ratios of torque and power factor of one of the motors of a cascade set, to the torque and power factor of a single motor.

Referred to $x'y'$ axes we have:

$x'$ co-ordinate $= {}_2F_1 \cos \alpha$ ; $y'$ co-ordinate $= 0$

Hence referred to $xy$ axes we have

$$x = {}_2F_1 \cos \alpha \cos \theta \, ; \quad y = - {}_2F_1 \cos \alpha \sin \theta$$

Therefore
$$x^2 + y^2 = {}_2F_1^2 \cos^2 \alpha = \frac{d^2 \cos^2 \theta}{(2\lambda_1\lambda_2 - 1)^2}$$

and
$$\text{OC} = \sqrt{(x^2 + y^2)} = \frac{d}{(2\lambda_1\lambda_2 - 1)} \cos \theta$$

This is in the form of the polar equation to a circle, hence the locus of C is a semicircle of radius $\dfrac{d}{2\lambda_1\lambda_2 - 1}$ with its centre on the $x$ axis distant $\dfrac{d}{2(2\lambda_1\lambda_2 - 1)}$ from the origin.*

Now the angle OCN is a right angle; hence, since ON lies along the $x$ axis, ON must be the diameter of the semicircle which gives the locus of C. Therefore N is a fixed point, distant $\dfrac{d}{(2\lambda_1\lambda_2 - 1)}$ from the origin.

But
$$\lambda_1\lambda_2 = 1 + \sigma$$

Therefore
$$\text{ON} = \frac{d}{2\sigma + 1} = \text{KL}$$

Hence the semicircles giving the locus of the points "a" and "c" are tangential at N.

The change of phase of the voltage applied to the auxiliary machine can be deduced from the diagram. The supply voltage is represented in phase by the OY axis, which is fixed; the P.D. applied to the auxiliary motor is represented in phase by the perpendicular to its magnetizing current, that is by the perpendicular to OD. Hence the difference in phase $= \angle \text{POD} = \beta$, say, (see Figs. 2 and 3).

Let
$$\angle \text{DOQ} = \gamma$$

Now GK is equal and parallel to OA

Therefore
$$\angle \text{GKL} = \angle \text{AOL} = (\alpha - \theta)$$

Again, joining GL, we have GL parallel to aN.

Therefore
$$\angle \text{KGL} = \angle \text{OaN} = \angle \text{aOY}' = 90 - \alpha$$

Also
$$\angle \text{GKL} = 180 - \left\{(\alpha - \theta) + (90 - \alpha)\right\} = 90 + \theta$$

Therefore
$$\angle \text{GML} = \theta$$

Hence, as the current changes from no load to standstill, $\theta$ varies from 0° to 90°.

The co-ordinates of D with respect to the $x'y'$ axes are:

$$x' = \lambda_2 \, {}_2F_1 \cos \alpha \, ; \quad y' = {}_2F_2 \, (\lambda_1\lambda_2 - 1)$$

Therefore
$$\tan \gamma = \frac{y'}{x'} = \frac{{}_2F_2 \, (\lambda_1\lambda_2 - 1)}{\lambda_2 \, {}_2F_1 \cos \alpha}$$
$$= \frac{(\lambda_1\lambda_2 - 1) \tan \alpha}{\lambda_1\lambda_2}$$

since $\lambda_1 \cdot {}_2F_2 = {}_2F_1 \sin \alpha$.

Now
$$\cos \alpha \sin \theta \, (2\lambda_1\lambda_2 - 1) = 2 \sin \alpha \cos \theta \, (\lambda_1\lambda_2 - 1)$$

Therefore
$$\tan \alpha = \frac{(2\lambda_1\lambda_2 - 1) \sin \theta}{2(\lambda_1\lambda_2 - 1) \cos \theta}$$
$$= \frac{(2\lambda_1\lambda_2 - 1)}{2(\lambda_1\lambda_2 - 1)} \tan \theta$$

Therefore
$$\tan \gamma = \frac{(\lambda_1\lambda_2 - 1)\,(2\lambda_1\lambda_2 - 1)}{2\lambda_1\lambda_2\,(\lambda_1\lambda_2 - 1)} \tan \theta$$
$$= \frac{2\sigma + 1}{2\sigma + 2} \tan \theta$$
$$= K \tan \theta \text{ (say)}$$

---

* It should be noted that although C lies on a semicircle on Oa$(= {}_2F_1)$ as diameter, this semicircle is only drawn to help in the construction of the diagram. It is not a fixed semicircle because its diameter ${}_2F_1$ is not fixed.

Hence, as the current varies from no load to standstill, $\gamma$ varies from 0° to 90°, and therefore the phase of the potential difference applied to the auxiliary motor relative to the supply potential difference, which is given by the angle $\beta (= \theta - \gamma)$, varies from 0° to a maximum, and then falls to 0° again.

The expression for $\beta$ is worked out as below, although it is of greater theoretical than practical value.

Let the quantities $r$, $R$, $c$ and $a$ have the significance shown in Fig. 7. Then

$$R = a \cos \theta$$

$$r^2 = R^2 + c^2 - 2Rc \cos \theta = a^2 \cos^2 \theta + c^2 - 2ac \cos^2 \theta$$

Therefore $$\cos^2 \theta = \frac{c^2 - r^2}{2ac - a^2}$$

and $$\tan^2 \theta = \frac{r^2 - (c - a)^2}{c^2 - r^2}$$

Again, $$\tan (\theta - \gamma) = \frac{\tan \theta - \tan \gamma}{1 + \tan \theta \tan \gamma} = \frac{(1 - K) \tan \theta}{1 + K \tan^2 \theta}$$

$$= \frac{(1 - K)\sqrt{\left[\frac{r^2 - (c - a)^2}{c^2 - r^2}\right]}}{(1 - K)\left\{\frac{r^2 - (c - a)^2}{c^2 - r^2}\right\}}$$

Therefore

$$\beta = (\theta - \gamma)$$

$$= \tan^{-1} \left[ \frac{(1 - K)\sqrt{\left[(c^2 - r^2)\left\{r^2 - (c - a)^2\right\}\right]}}{(c^2 - r^2) - K\left\{r^2 - (c - a)^2\right\}} \right]$$

This is equal to zero when

$r = (c - a)$, the no-load current,

or when $r = c$, the standstill current.

# PROCEEDINGS OF THE INSTITUTION.

## 24TH MEETING OF THE WIRELESS SECTION, 8 NOVEMBER, 1922.

(Held in the Institution Lecture Theatre.)

**Professor G. W. O. Howe, D.Sc.,** Chairman of the Wireless Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 7th June, 1922, were taken as read, and were confirmed and signed.

A paper by Mr. R. L. Smith-Rose, M.Sc., Associate Member, and Mr. R. H. Barfield, B.Sc., Student, entitled "The Effect of Local Conditions on Radio Direction-Finding Installations" (see page 179), was read and discussed and the meeting terminated at 7.45 p.m.

## 687TH ORDINARY MEETING, 16 NOVEMBER, 1922.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 2nd November, 1922, were taken as read, and were confirmed and signed.

Messrs. J. W. Fyfe and A. H. Allen were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

### ELECTIONS.

*Members.*

Clark, George Muirhead.
Farmer, Frank Malcolm, M.E.

*Associate Members.*

Allen, Francis John C.
Andean, Thomas John.
Andrews, Edward.
Bagnold, Ralph Alger, Capt., R.C.S.
Banks, John
Baxter, William.
Boelsterli, Arthur.
Brown, Arthur.
Bryant, Harold Samuel.
Clark, Frederick Henry.
Clissold, George William U.
Cooke-Smith, Henry.
Currie, Duncan Douglas.
do Amaral, Augusto Basto F.

*Associate Members*—continued.

Earnshaw, Vincent Rees.
Eugster, Hans.
Ford, Albert Edwin.
Frampton, Frank Edward.
Griffiths, William.
Holbeach, Constantine Hugh.
Joscelyne, Alfred Bamford.
Lee, Robert Henry.
Minton, Richard Caldwell, B.Sc.
Newton, Charles Ernest.
Noyes, Henry Sebastian.
Orling, Axel.
Osborn, William Marshall.
Parsons, Reginald Cole, B.Sc.
Pearse, Harold Leslie.
Ross, William.
Rowell, William Nelson.
Sell, Lawrence Jordan.
Smith, Dugald, B.Sc. (Eng.).
Triggs, Edward Harold H.

*Graduates.*

Atkinson, Wellesley Sharpe.
Bassett-Lowke, Harold Austin.
Bournes, Norman.
Bunting, Rowland.
Cook, Frederick Charles.
Dixon, Charles Douglas H.
Earle, Robert Erasmus.
Faulkner, Arthur Spencer.
Llewellyn-Jones, Ivor.
Lowe, Walter.
McGrath, Francis Albert, B.E.
Rogers, Henry Kenneth.
Rowson, Leslie.
Witt, Sidney Herbert.

*Students.*

Abbott, Albert James.
Anderson, Charles.
Anderson, John Robertson.
Andrew, Thomas Stuart.
Baggaley, Cyril Frank.
Ball, Reginald Donahoe.
Bell, William Henry H.
Benjamin, Albert Hansen.
Bennett, Wilfred.
Booth, William Leslie.
Bowers, Wilfred Edward H.
Bowker, Eric George.
Brewer, Arthur.
Brewin, James Edwin.
Britnell, Wilfred Varney.
Bryan, Ernest Alfred J.
Carter, Charles John E.
Chakravarti, Girindra Narayan.
Chalk, Stewart Leonard.
Clarke, Henry Rowland.
Clewett, William Henry.
Clinton, James Stanley.
Cocks, Maurice Hubert.
Collyns, Charles Henry A.
Cooke, Conrad Reginald.
Couch, Charles John.
Das, Jatindranath.
Datta, Naren, B.Sc.
Donaldson, Thomas.
Eccleston, Robert John.
Ellis, Arthur Eric.
Ellis, Cecil Maurice.
Ellis, Harold.
Fewings, William Francis.
Fothergill, John Buddle.
Francis, Richard Brynmor.
Goodman, Reginald Alfred.
Gresswell, William Finlay.
Hardy, George Gordon.
Hellier, William Herbert M.
Heslop, John Pattison.
Hogg, William.
Horsfall, Leslie A.
Innes, James Albert.
Johnson, Eric Mark.
Keeley, Donald.
Lewis, Walter.
Lisle, Patrick St. John.
Lockett, Thomas Herbert.
McCulloch, Reginald Andrew.
McNab, John.
Manning, Charles Joseph.
Matthews, Leslie Albert.
Miller, William Henry.
Mitchell, Henry Lloyd.
Mitchell, Wallis.
Morgan, Cecil Montagu.
Mossman, Conrade Eric.
Parsons, Albert George.
Pearce, Ivor Stanley.
Peel, Edward Ullathorne.
Penn, Herbert Austin.
Reed, Arthur Weston.
Rees, Handel.
Reynolds, Leigh Travis.
Ross, Burton William.
Ryder, John Hampson, B.Eng.
Scott, William George, B.Sc. (Eng.).
Simpson, Henry Greeff.
Smith, Cyril Belfield.
Smithson, Alfred.
Stainsby, James William.
Tucker, Dan Keith.
Wheeler, Henry.
Williams, Alec Duncan.
Williamson, Arthur.
Wolfe, Standish Smythe.
Wood, George William.
Woodford, Charles George A.

### TRANSFERS.

*Associate Member to Member.*

Davis, Albert Lewis, Capt., R.A.F.
Lee, Harrie Tomlinson.
Slater, John Mackey L.
Wilson, William.

*Associate to Member.*

Bell, John Edward.
Starling, Frank Henry.
Swallow, Maurice Gustave S.

*Graduate to Associate Member.*

Berriman, Robert Harrold.
Calogreedy, Henry Charles.
Davison, Russell Hawes.
Firth, Charles Roy H., Lieut.
Larkworthy, Ralph.
Leaver, Henry.
Messer, William Gustave.
Rogers, Arthur Harry E.
Sparks, Cedric Harold.

*Student to Associate Member.*

Balmford, Edgar.
Field, Harold Victor.
Millner, William, B.Sc.

*Associate to Associate Member.*

Barnes, Cuthbert Wheeldon.
Naftel, Percy Hartley.
Read, Richard Francis.
Smart, William Charles.

*Student to Graduate.*

Armstrong, Stanley Ignatius.
Blazey, Norman Claude.
Boldy, Tigran David.
Butler, Archibald Stephen.
Gabbott, Thomas.
Molle, George William.
Morcom, Herbert Geoffrey.

The following list of donations was taken as read, and the thanks of the meeting were accorded to the donors :—

*Library.*—The Air Ministry (Meteorological Office), The American Rolling Mill Company, The Astronomer Royal, A. H. Avery, Lieut.-Col. B. C. Battye, Messrs. Benn Brothers, Ltd., E. Bennett, Ch. Beranger, Messrs. Blackie & Son, Ltd., The Borough Electrical Engineer of Stepney, The British Engineering Standards Association, The Bureau of Mines (British Columbia), F. W. Carter, The Chief Inspector of Factories and Workshops, Messrs. Constable & Co., Ltd., The Electrical Press, Ltd., W. Haddon, P. J. Haler, The High Commissioner of the Union of South Africa, The Imperial Mineral Resources Bureau, The Institution of Professional Civil Servants, The Institution of Railway Signal Engineers, The Institution of Royal Engineers, The John Fritz Medal Board of Award, P. Kemp, A. E. Kennelly, The Lancashire and Cheshire Coal Research Association, Messrs. S. Lattes & Co., Lloyd's Register of Shipping, Messrs. Longmans, Green & Co., F. W. Main, J. W. Meares, C.I.E., Messrs. Oerlikon, Ltd., Lieut.-Col. W. A. J. O'Meara, C.M.G., R.E., L. Oulton, Pan-American Petroleum and Transport Co., E. Parry, L. J. Peters, Messrs. Sir Isaac Pitman & Sons, Ltd., Messrs. Radio Instruments, Ltd., Messrs. S. Rentell & Co., Ltd., The Signals Experimental Establishment (Woolwich), C. F. Smith, The Surveyor-General of India, Messrs. E. & F. N. Spon, Ltd., W. T. Taylor, Union d'Électricité, H. E. Wimperis, The Wireless Press, Ltd., and A. P. Young.

**The President :** I have to announce that the Council have unanimously elected Professor J. A. Fleming an Honorary Member of the Institution. Dr. Fleming is so well known to all of you that almost anything I could say would be superfluous, but the fact that one of the first announcements I have to make as President is that he has been elected an Honorary Member is a great pleasure to me, particularly because of his researches in connection with the thermionic valve.

I have also to announce that, with the object of encouraging more spontaneous discussion, in future not more than two or three members will be invited officially to take part in discussions and that the Council will rely on other members coming forward to speak.

A paper by the late Dr. Gisbert Kapp, Past-President, entitled "The Improvement of Power Factor" (see page 89), was read by Prof. Miles Walker and discussed, and the meeting terminated at 7.45 p.m.

# A DIRECT-READING THERMIONIC VOLTMETER, AND ITS APPLICATIONS.

By E. B. Moullin, M.A.

(*Paper received 2nd November, and read before the* Wireless Section *6th December*, 1922.)

### Summary.

The conditions suitable for constructing a sensitive direct-reading voltmeter from a triode rectifier are discussed and two distinct forms of completed thermionic voltmeter are described. The power absorbed by a rectifier is discussed theoretically, and a description is given of the experimental methods of measuring the effective resistance of a thermionic voltmeter. Possible causes of frequency errors in the calibration of the voltmeter are considered and the results of experiments are quoted, showing that a calibration made at low frequencies is reliable up to at least one million periods per second. Several typical illustrations are given of the uses of a thermionic voltmeter in measurements at both high and low frequencies.

### Table of Contents.

(1) Introduction.
(2) Conditions suitable for using a triode rectifier as a direct-reading voltmeter.
(3) Description of two types of completed instruments.
(4) The power delivered by an alternating E.M.F. to an asymmetric conductor.
(5) Method of calibration and accuracy tests at high frequency.
(6) Some applications of the thermionic voltmeter.
  (*a*) Use as a high-frequency milliammeter.
  (*b*) Direct measurement of very small self and mutual inductances.
  (*c*) Direct measurement of high-frequency resistance.
  (*d*) Measurement of the amplification produced by triode amplifiers.
  (*e*) Measurement of signal strengths in wireless telegraphy.
  (*f*) Determination of the power factor of condensers.
  (*g*) Measurement of stray magnetic fields.
  (*h*) Miscellaneous.

## (1) Introduction.

There are many occasions in alternating-current work when it is desirable to measure small electromotive forces of the order of one or two volts; such measurements are attended with great difficulty in cases where it is essential that they shall not absorb any appreciable power from the circuit that is being tested. Practically the only instrument hitherto available has been that most useful piece of apparatus an alternating-current potentiometer, but the use of this is precluded in measurements at high frequency.

The well-known thermionic vacuum tube forms a most convenient method of measuring alternating electromotive forces of any frequency, because owing to its asymmetric conductivity an alternating E.M.F., of which the mean value is zero, produces an alternating current whose mean value is not zero, and the said mean value is readily measured by an ordinary milliammeter or micro-ammeter. A rectifier and galvanometer have long been used in laboratory measurements as a rough indicator for high-frequency work.

If a suitably arranged three-electrode vacuum tube is used as the asymmetric conductor, the measurements need not absorb any power from the circuit that is tested, for the power absorbed by the micro-ammeter is provided by a subsidiary battery.

The two methods of using the triode valve as a rectifier are well known: one method employs the curvature of the anode current/grid potential characteristic, while the other method employs the curvature of the grid current/grid potential characteristic.

## (2) Conditions Suitable for using a Triode Rectifier as a Direct-reading Voltmeter.

There exists, as well as the change of mean anode current that arises from the application of an alternating E.M.F. between grid and filament, an anode current produced solely by the anode battery; consequently, unless the change of mean anode current arising from the alternating E.M.F. that is to be measured is of the same order as the anode current flowing under the action of the anode battery, it cannot be satisfactorily measured by a galvanometer placed direct in the anode circuit. This is particularly the case when employing the curvature of the anode current characteristic under the conditions which make for the greatest possible change of mean anode current for a given alternating E.M.F. applied to the grid. For example, an anode battery of 50 or 60 V will, in an R triode, produce an anode current of about 1 000 $\mu$A, and an E.M.F. of 1·5 volts (R.M.S.) applied to the grid will then increase the mean anode current by about 30 $\mu$A. In order that this comparatively small change in mean anode current can be accurately measured, some balance method must be employed.*

A balance method, though very suitable for many laboratory measurements, does not lend itself to the construction of a simple and portable direct-reading voltmeter. In such an instrument, unlike a rectifier for wireless signals, the aim is to make the change of mean anode current consequent upon the application to the grid of some specified E.M.F. as large as possible in comparison with the anode current flowing under the action of the anode battery.

---

* See E. B. Moullin and L. B. Turner: "The Thermionic Triode as Rectifier," *Journal I.E.E.*, 1922, vol. 60, p. 708.

With a cumulative grid rectifier, an alternating E.M.F. of 3 volts can be made to produce a decrease of mean anode current of about 500 $\mu$A when the anode current produced by the anode battery is about 1 000 $\mu$A; consequently, a galvanometer placed direct in the anode circuit can be used to measure the change produced by the application of an alternating E.M.F., and there is no need to use a balance method.

An anode curvature rectifier may be employed without balance method if the usual anode battery is dispensed with, and the anode connected through a galvanometer to the positive side of the filament. An E.M.F. of 1·5 volts (R.M.S.) applied to the grid will then produce an increase of mean anode current of about 10$\mu$ A. If a 50-volt anode battery had been employed, this increase instead of being 10 $\mu$A would have been 30 $\mu$A, which is about 4 per cent of the anode current flowing under the action of the anode battery; but the 10 $\mu$A change with no anode battery is a 400 per cent increase on the anode current flowing when the anode is simply connected to the positive side of the filament, a condition particularly suitable for using a triode as a simple voltmeter. The lack of anode battery is not only suitable in this respect but it obviously increases the portability of the instrument.

### (3) Description of Completed Instruments.

Fig. 1 shows a completed instrument working with grid rectification, and Fig. 2 a diagram of connections. It is found that the calibration is inappreciably affected by small changes of anode or filament voltages, so that there is no necessity to reproduce accurately the conditions obtaining at the time of calibration * Since the change of mean anode current consequent upon the application of a given E.M.F. to the grid is sensibly independent of small changes of anode potential, it is possible to adjust for these small changes by means of the zero adjuster of the galvanometer. With the valve switched on and the anode battery connected, the pointer is simply brought to the zero of the scale, which in this case corresponds to the full deflection of the instrument.* One special advantage of this type of instrument is that it is unaffected by the existence of a steady potential difference between its terminals; it can, in consequence, be used to measure an alternating E.M.F. superposed upon a steady E.M.F. of large or small value.

Fig. 3 shows an instrument utilizing anode current curvature for rectification. No separate anode battery is employed and all that is required to complete the instrument for use is a 6-volt filament battery. The instrument is very robust mechanically and, unlike thermo-couples, it cannot be injured by an overload. It is also as easy to use and almost as portable as an ordinary direct-current voltmeter.

Fig. 4 shows a diagram of connections, from which it will be seen that the 6-volt filament battery is not used to apply 6 volts to the filament, but to provide a means of making the grid potential 1·6 V negative, in order to reduce grid damping to a negligible amount. This method of fixing the grid potential allows it to be made about 0·25 V more negative than it could have been if a single small dry cell were used for the purpose, and it also obviates the risk of the calibration being upset by the deterioration of a small cell.

In order to ensure an indefinitely long life to the valve, only 3·6 V is applied to the filament; this is also the case with the cumulative grid type instrument already described.

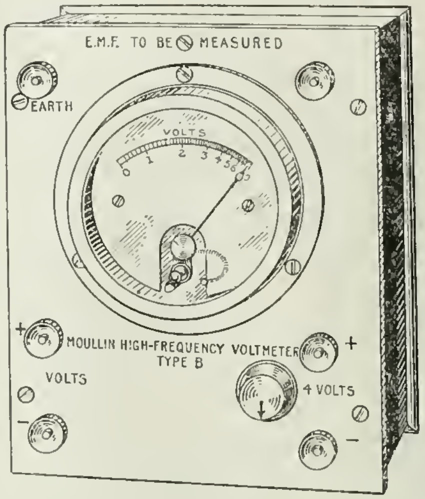


Fig. 1.

The rate of change of mean anode current with respect to alternating grid potential tends to increase and so a high resistance is inserted in the anode circuit with a view to improving the linearity of the scale and thereby increasing the range of the instrument; it does not, however, reduce the sensitivity of the first part of the scale. It is readily seen that by causing the increasing mean anode current to pass through a high resistance the mean potential of the anode is decreased by an amount that is proportional to the increase of mean anode current. The rate of increase of mean anode current is lessened by the reduction of anode potential, and by a suitable choice of anode resistance the volt scale can be made as nearly linear as may be desired.

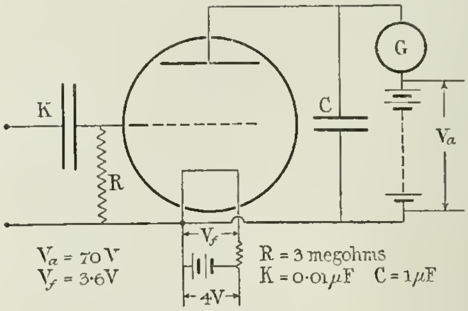


Fig. 2.

A typical calibration curve is reproduced in Fig. 5 and is seen to be very nearly straight over the greater part of the range. The voltmeter is of course used without a calibration curve and, as may be seen in Fig. 3, its scale is engraved direct in volts.

---

* For a more detailed description of this instrument, see *Wireless World and Radio Review*, 1922, vol. 10, p. 1.

Since the filament battery is the only variable factor in the whole instrument the constancy of the calibration depends on it alone. The exact conditions obtaining at the time of calibration are readily reproduced by means of the filament rheostat and the indications of the galvanometer. Having ascertained that a conducting path exists between the "volt terminals" of the instrument so as to ensure that the potential of the grid will be fixed, the valve is switched on and the filament rheostat adjusted so as to bring the galvanometer to the zero of the volt scale, which, as can be seen in Fig. 3, does not correspond to the zero of the galvanometer, marked "A." When this adjustment has been made, the anode current flowing is the same as at the time of calibration, and as this depends solely on the grid, filament and anode potentials, all of which in this instrument depend on the filament current only, the conditions obtaining at calibration are accurately reproduced. If the filament current had been greater than at the time of calibration the galvanometer would have deflected further than the zero of the volt scale, and vice versa.

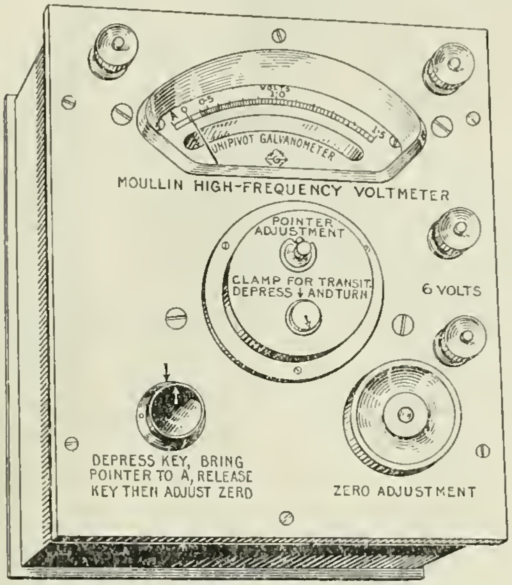

VOLTS
0·5
1·0
1·5
UNIPIVOT GALVANOMETER
MOULLIN HIGH-FREQUENCY VOLTMETER
POINTER ADJUSTMENT
CLAMP FOR TRANSIT DEPRESS ↓ AND TURN
6 VOLTS
DEPRESS KEY, BRING POINTER TO A, RELEASE KEY THEN ADJUST ZERO
ZERO ADJUSTMENT

FIG. 3.

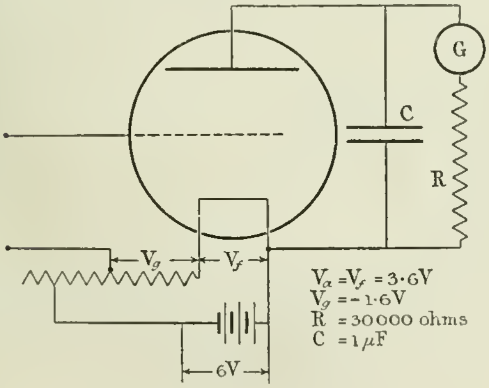


FIG. 4.

It will be noticed that a conducting path must at all times exist between the "volt terminals" of the instrument, for otherwise the grid potential will not be correct. For example, this type of voltmeter cannot be used to measure the potential difference across one of two condensers in series, for it is then converted into a cumulative grid rectifier, and the calibration is upset. Also the calibration is obviously upset if any steady potential difference exists between the "volt terminals." Neither of these slight disabilities is shared by the form of voltmeter shown in Fig. 1, so that there are certain points in favour of the less portable form of instrument.

A triode can be used to measure an alternating E.M.F. by employing what is usually called the "slide-back method of measurement." It has several times been shown that the value of the "slide-back voltage" is not a direct measure of the E.M.F. applied to the valve; consequently, unless calibrated, the slide-back method cannot be considered to be anything but a rough indicator, and if calibrated it suffers from the disability of having a large personal factor in deciding on the appropriate slide-back. It is difficult to make direct reading and is not very portable, as it entails cumbersome grid and anode batteries and a d.c. voltmeter, as well as a galvanometer.

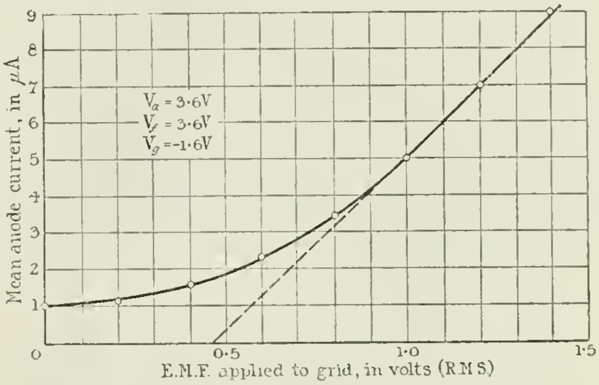


FIG. 5.

F. Trautwein has described * a form of voltmeter in which, like the slide-back, the effect of the anode battery is nullified by making the grid 10 or 11 V negative. Instead of making the grid still more negative when the E.M.F. is applied, and so again reducing the anode current to zero, the mean anode current is taken as a measure of the E.M.F. The portability is again impaired by cumbersome batteries, and the early part of the calibration must be affected appreciably by small changes in battery voltage.

Messrs. A. E. and L. Bloch have described † a voltmeter using cumulative grid rectification, in which the

---

* *Telegraph und Fernsprech Technik*, 1921, vol. 10, p. 81.

† *Bulletin de la Société française des Electriciens*, 1920, vol. 10, p. 9.

change of mean anode current, consequent upon the application of an alternating E.M.F. to the grid, is measured by a balance method equivalent to that referred to in Section (2) above. The voltmeter proper is preceded by a two-stage resistance amplifier, the amplification of which must depend to a great extent upon the frequency. Messrs. Bloch recommend that the instrument should always be calibrated at the frequency to be used.

The outstanding feature of the author's form of grid-type voltmeter is that the anode battery is chosen so that the decrease of mean anode current bears a maximum ratio to the anode current produced by the anode battery, thus allowing balance methods to be dispensed with and the instrument dial to be calibrated direct. This is also the condition which makes the calibration sensibly independent of small changes in the E.M.F.'s of the batteries or in the grid leak resistance. A very simple direct-reading instrument results, and no special care need be taken to reproduce closely the calibrating conditions. The outstanding points about the author's form of anode type voltmeter are, first, the complete absence of separate anode or grid batteries, the only extraneous apparatus required being a nominally 6-volt accumulator: and secondly, the exact reproduction of the calibrating conditions by the indication of the galvanometer. So far as the author is aware, the methods of application and construction of both types are original, and he believes that they make simpler and more portable instruments than anything yet described.

## (4) THE POWER DELIVERED BY AN ALTERNATING E.M.F. TO AN ASYMMETRIC CONDUCTOR.

The two great advantages of a thermionic voltmeter are, first, that its readings are independent of frequency, and, secondly, but of no less importance, that it can be made to absorb negligible power from a circuit. The effective resistance of both types of instrument can be measured, but it is interesting to obtain a theoretical expression for the power absorbed by an asymmetric conductor.

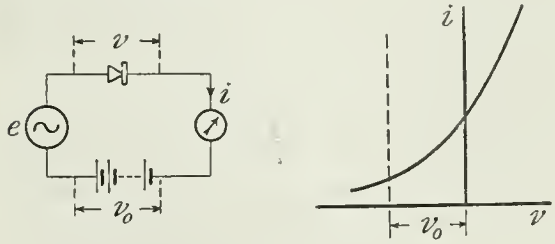


FIG. 6.

Let the asymmetric conductor (Fig. 6) have a curved characteristic $i = f(v)$ which can be represented by a convergent infinite series.

Then $$v = v_0 + e$$

and $$i = f(v_0) + ef'(v_0) + \frac{e^2}{2\,!}f''(v_0) + \frac{e^3}{3\,!}f'''(v_0) + \dots$$

Let $$e = a \sin pt$$
then
$$i = f(v_0) + a \sin pt f'(v_0) + \frac{a^2 \sin^2 pt}{2\,!}f''(v_0) + \frac{a^3 \sin^3 pt}{3\,!}f'''(v_0) + \dots$$
and
$$ie = a \sin pt f(v_0) + a^2 \sin^2 pt f'(v_0) + \frac{a^3 \sin^3 pt}{2\,!}f''(v_0) + \frac{a^4 \sin^4 pt}{3\,!}f'''(v_0) + \dots$$
$$\therefore \frac{\int_0^{2\pi/p} ie\,dt}{2\pi/p} = \frac{a^2}{2}f'(v_0) + \frac{a^4}{16}f'''(v_0) + \dots$$
$$\therefore \text{mean power} = \tfrac{1}{2}a^2\left\{f'(v_0) + \tfrac{1}{8}a^2 f'''(v_0)\right\}$$
$$= \mathcal{E}^2\left\{f'(v_0) + \tfrac{1}{4}\mathcal{E}^2 f'''(v_0)\right\} \quad . \quad . \quad . \quad . \quad (1)$$
where $\mathcal{E}$ = mean-square value of $e$.

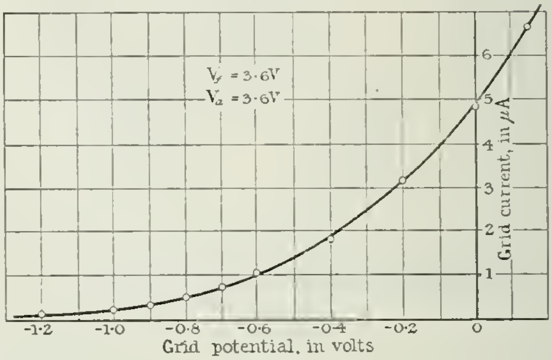


FIG. 7.

The effective resistance is, of course, not a constant but is a function of $\mathcal{E}^2$.

Now, as is well known, the mean value of the current is given by the expression
$$I = \tfrac{1}{2}\mathcal{E}^2 f''(v_0) + \tfrac{1}{16}\mathcal{E}^4 f''''(v_0) + \dots \quad . \quad . \quad (2)$$

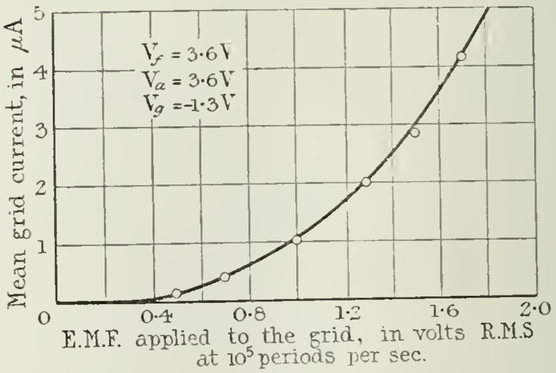


FIG. 8.

so that it is seen that the mean current taken by a rectifier is no indication of the power absorbed by it from the source of alternating E.M.F., except in so far as there may be a relation between $f'(v_0)$ and $f''(v_0)$, $f'''(v_0)$ and $f''''(v_0)$.

Direct high-frequency measurements have been made of the effective resistance of an anode-type voltmeter.

The grid current/grid potential curve for the instrument tested is shown in Fig. 7, while Fig. 8 shows the mean grid current as a function of the E.M.F. (at $10^5$ periods per sec.) applied to the grid. From Fig. 7, with or without the help of Fig. 8, it may be found that for a mean grid potential of 1·3 V (negative) the value of $f'(v_0) \fallingdotseq 0{\cdot}35\ \mu$A/V and that the value of $f'''(v_0) \fallingdotseq 4\mu$A/V/V/V; and hence, from (1) above, the effective resistance $\fallingdotseq \dfrac{1}{0\cdot 35 + \mathcal{E}^2}$ megohms. This is approximately 0·75 megohm if $\mathcal{E} = 1$ V, and 0·4 megohm if $\mathcal{E} = 1\cdot 5$ V.

To make a direct high-frequency test of the effective resistance, a circuit was arranged as in Fig. 9 in which $L = 480\ \mu$H, and $C = 6\,270\ \mu\mu$F, and $R$ measured at $10^5$ periods per sec. (p.p.s.) was 15 ohms. The circuit was fed by a sustained alternating E.M.F. at $10^5$ p.p.s., the current in the circuit was measured by a vacuo thermo-junction, and the resonance potential developed across the condenser was measured by an anode-type thermionic voltmeter.

By observing the thermo-junction reading with and without the voltmeter connected across the condenser it is possible to calculate the effective resistance of the voltmeter. For let the effective resistance of the voltmeter be denoted by $r$, then the impedance of the circuit consisting of $L$ and $R$ in series with $C$ and $r$ in parallel is given by

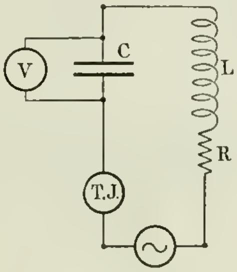


FIG. 9.

$$Z = \sqrt{\left[R^2 + \frac{\omega^2L^2 + 2Rr}{1 + r^2\omega^2C^2}\right]} \text{ when } \omega L = \frac{1}{\omega C}$$
$$\fallingdotseq R\sqrt{\left[1 + \frac{2}{Rr\omega^2C^2}\right]}$$
$$\fallingdotseq R + \frac{1}{r\omega^2C^2}$$

Hence the proportional increase of impedance caused by placing $r$ in parallel with $C$ is equal to

$$\frac{1}{rR\omega^2C^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Thus, in the particular circuit tested, this proportionate increase of impedance is equal to $4\cdot 3 \times 10^3/r$. It was found that by connecting the voltmeter across $C$, the current as measured by the thermo-junction was reduced by an amount that was certainly less than 1 per cent, when the value of the current was such that the potential difference across $C$ was 1·75 V(R.M.S.). Now, if $r$ had been 0·5 megohm, by (3) above the decrease of current would have been 0·86 per cent, so that even at full scale the effective resistance of the voltmeter is at least half a megohm, and much more at half scale. The power taken at full scale is consequently not more than 6 microwatts. A megohm resistance substituted for the voltmeter caused a decrease in current that was approximately the same as that caused by the connection of the instrument. It may be noted that, in the particular instrument tested, the mean grid potential was only 1·3 V negative, whereas in later instruments it is always made 1·6 V negative, with a consequent increase in the effective resistance.

The effective resistance of the cumulative grid type of voltmeter is slightly greater than in the anode type, because the mean grid potential becomes more and more negative with an increasing alternating E.M.F. applied to the grid; in fact, the calibration shows that with an E.M.F. of 3 V (R.M.S.) applied to the grid, the mean grid potential must be at least 2·5 V negative.

The effective resistance of this type is conveniently measured by making two calibration curves at low frequency: one with a grid condenser, the impedance of which is negligible in comparison with the resistance of the grid leak, and one with a condenser of known and appreciable impedance. From the difference between the two calibrations the effective resistance can readily be calculated.*

As the resistance of either type of voltmeter is at least half a megohm, there are few measurements in which it is necessary to allow for the decrement thereby introduced, as the following example will illustrate.

The decrement introduced into an oscillatory circuit LC by a condenser leak of high resistance $r$ is

$$\delta = \frac{\pi}{r}\sqrt{\left(\frac{L}{C}\right)}$$

Now suppose $L = 2\,000\ \mu$H and $C = 200\ \mu\mu$F (corresponding to $\lambda = 1\,200$ m) and that $r = 0\cdot 75$ megohm; then $\delta \fallingdotseq 0\cdot 015$.

In cases where the decrement introduced by the voltmeter is of importance it can, as already seen, be determined with sufficient accuracy to enable the necessary allowance to be made.

### (5) METHOD OF CALIBRATION, AND ACCURACY TESTS AT HIGH FREQUENCIES.†

A convenient method of calibrating a voltmeter is by means of a potentiometer slide-wire of known resistance which carries a known alternating current of any frequency. The method is shown diagrammatically in Fig. 10. E is a source of alternating current at high or low frequency. A is an ammeter and R is the potential slide, which may conveniently be arranged in 1-ohm steps. Since in a properly designed thermionic voltmeter the calibration is necessarily independent of frequency, it is most conveniently effected at the low frequencies of ordinary commercial power supply, but, if preferred, it can of course be made in the same manner at high frequencies. So long as adequate means are provided to ensure that the alternating fluctuations of anode potential are negligible at the highest frequency likely to be met with, then a calibration made at low frequency can always be trusted.

---

* See "A Sensitive Direct-reading Voltmeter and Ammeter for High Frequencies," *Wireless World and Radio Review*, 1922, vol. 10, p. 1.

† The experiments described in this paper were carried out in the Engineering Laboratory, Cambridge, with facilities put at the author's disposal by Professor C. E. Inglis.

The internal capacities of the triode may cause a quadphase grid current to flow which might appreciably lower the P.D. to be measured, and also the internal capacity will enhance the alternating component of anode current, but so long as a sufficiently large condenser is connected between the anode and the filament there will be no fluctuation of anode potential, and neither internal capacities nor anode-circuit impedances can upset the low-frequency calibration. Many high-frequency tests of the calibration have been made and no appreciable change with frequency is observable. Figs. 11 and 12 relate to high-frequency tests which were made by measuring the P.D. developed across known resistances by the passage through them of a known high-frequency current. The resistances were constructed from short lengths of fine Eureka wire (36 S.W.G.) and the current was measured by means of a fine wire vacuum thermo-junction.

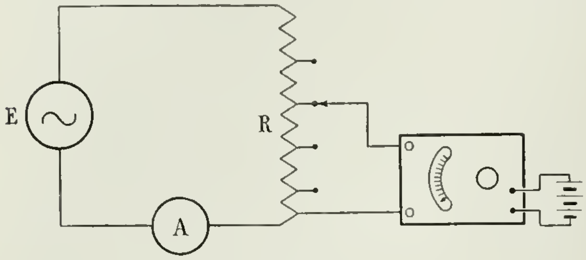


FIG. 10.

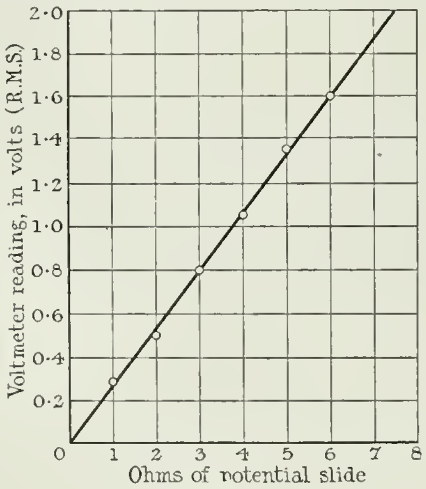


FIG. 11.

Fig. 11 shows a relative calibration test of the whole scale at $10^5$ p.p.s. The applied E.M.F., as measured by the resistance included between the potential terminals of the potentiometer, is plotted horizontally and the voltmeter reading vertically; it can be seen that the low-frequency calibration is, over the whole range of the scale, truly proportional to the high-frequency E.M.F. applied to the instrument. Fig. 12 shows the result of a test on an anode-type voltmeter of the calibration made at 90 p.p.s.; the percentage inaccuracy of the full-scale reading is shown for frequencies up to half a million per second. Up to $3 \times 10^5$ p.p.s. the 90 p.p.s. calibration is certainly correct to less than 1 per cent; at $8 \times 10^5$ p.p.s. ($\lambda = 380$ m) the low-frequency calibration seems to be between 3 and 4 per cent too low. This error could not be corrected by indefinitely increasing the shunting condenser in the anode circuit, and it is very probably not due to the voltmeter at all but to the tendency of the thermo-junction to read high with increasing frequency. Of many other high-frequency tests of the voltmeter two more may be cited, one relating to the circuit of Fig. 9 and one to an aerial resistance test. In Fig. 9 the value of the P.D. across C calculated from the capacity, the frequency, and the measured current was 1·7 V, whereas the P.D. observed by the voltmeter was 1·75 V. The resistance at $8 \times 10^5$ p.p.s. of a small aerial was measured both by substitution and by injecting a known E.M.F. and measuring by means of the voltmeter the current produced. The substitution method gave the resistance as 30 ohms and the voltmeter method as 27·5 ohms.

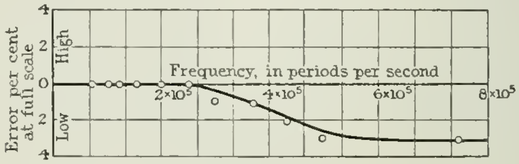


FIG. 12.

The tests and examples quoted above are probably sufficient to prove that the calibration made at low frequencies can certainly be trusted up to very high frequencies, if adequate precautions are taken in the design and construction of the instrument. It has been suggested that low-frequency tests of the general theory of rectification are not applicable to the conditions obtaining at high frequencies;* but the above tests would suggest that this is not the case.

It is no doubt possible to obtain a mathematical expression for the extent of the error produced by the presence in the anode circuit of some stated amount of impedance; but as this impedance can always be indefinitely reduced by a shunting condenser, and in practice will always be so reduced, the result of such an investigation would be of no practical and of little theoretical interest.

That the presence in the anode circuit of a small impedance can have but very small effect on the calibration can be seen in general terms, for the small fluctuations of anode potential must be sensibly in quadphase with the fluctuations of grid potential, and so add and subtract most from the anode current just at the time when it is near its mean value. In the anode type of instrument described above we may, with great accuracy, assume that current flows only during the positive half-cycle of E.M.F. If the anode-potential fluctuations were exactly in quadphase with the grid potential, then there would be no net change in the area of the half-cycle of anode current. The error must be roughly proportional to the amount by which the anode current is de-phased by the impedance, or to the ratio between the impedance and the mean value of the anode slope resistance. The mean anode slope resistance is about 1 megohm, so that to produce a phase angle of one-tenth of a degree would need, at $10^5$ p.p.s., an inductance of $200\,\mu$H.

---

* See discussion on "The Thermionic Triode as Rectifier," *Journal I.E.E.*, 1922, vol. 60, p. 720.

### (6) Some Applications of the Thermionic Voltmeter.

A low-reading alternating-current voltmeter of sensibly infinite resistance has a wide range of applications for all sorts of measurements whether at wireless frequencies or telephonic frequencies, or at the frequencies of ordinary commercial power supply. A few typical applications will be dealt with as follows.

(*a*) *As a high-frequency milliammeter.*—By measuring the potential developed across a known inductance or capacity, the current can be calculated if the frequency is known, and in this way the instrument can be used to measure extremely small currents. For example, at a frequency of $10^5$ p.p.s. the current required to develop a P.D. of 1 volt across an inductance of $10\,000\,\mu$H is about $160\,\mu$A. Now, with the most sensitive thermo-junction and portable galvanometer set obtainable, the smallest current that can be measured with the same accuracy with which 1 volt can be measured, on either of the voltmeters described above, is about $5\,000\,\mu$A ; so that under reasonably favourable conditions the voltmeter used as an ammeter gives a sensitivity some 30 times as great as the best thermo-junction set and is equally portable. But, whereas a thermo-junction is very easily burnt out by a small overload, the thermionic voltmeter cannot be damaged by any amount of overloading. It is obvious that the sensitivity may be indefinitely increased by interposing a calibrated amplifier between the voltmeter and the E.M.F. to be measured, but the above example was intended to show the sensitivity of the voltmeter itself without the assistance of extraneous apparatus. [For an example of its use with an amplifier see (*e*) below.] Its superior sensitivity as compared with that of a thermo-junction is often a matter of great practical convenience ; for instance, the voltmeter can always be used as an indicator of resonance in a circuit energized inductively from an ordinary buzzer-driven wave-meter. The uniformity of the scale makes it a most convenient instrument for use in plotting resonance curves or for measuring resistances by a substitution method.

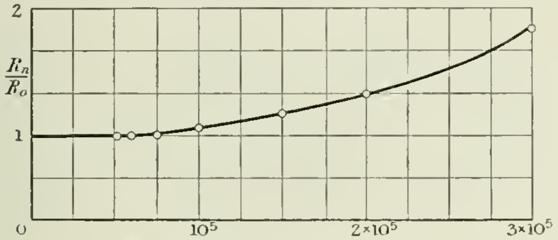


FIG. 13.

(*b*) *Direct measurement of very small self and mutual inductances.*—Inductances of the order of a microhenry are as a rule not readily measured either by bridge or resonance methods, but by passing through them a high-frequency current of some $\frac{1}{2}$ ampere in value they can be measured directly by the use of the voltmeter.

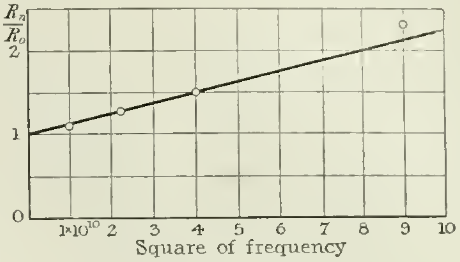


FIG. 14.

As an example, a coil was made consisting of two turns of 32 S.W.G. wire, 6 cm in diameter, the calculated value of the inductance being $1\cdot86\,\mu$H. The value measured by the voltmeter and an ammeter was $1\cdot80\,\mu$H at $1\cdot5\times10^5$ p.p.s. Interesting measurements could perhaps in this way be made as to the amount by which the inductance decreases as the frequency is increased.

The same method has been used to measure the value of small mutual inductances, either by observing the E.M.F. set up in one coil by a known current in the other, or by measuring the self-inductance of the two coils joined in series. A mutual inductance of $0\cdot8\,\mu$H has been successfully measured in this manner. The instrument is also useful for measuring the impedance-drop across dynamometer ammeters or current transformers.

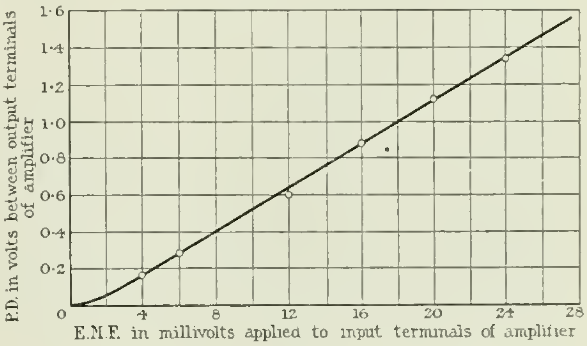


FIG. 15.

(*c*) *Direct measurement of high-frequency resistance.*—The resistance of a conductor can be measured by the same method as that just described for measuring inductance ; since the "skin effect" is only appreciable in fairly coarse wires it is necessary to use a considerable length unless a high-frequency current of several amperes is available. This involves a difficulty, for a foot or two of wire must, at high frequencies, have a reactance comparable with its resistance, and if the length of wire is doubled back on itself to minimize its reactance the axial symmetry of the current distribution will be disturbed.

As an example of the method the resistance of a doubled length of 18 S.W.G. Eureka wire has been measured at various high frequencies. Fig. 13 exhibits the observed values of the ratio $R_n/R_0$ plotted against the frequency, and Fig. 14 the value of $R_n/R_0$ plotted against the square of the frequency. The relation between resistance and frequency for this doubled length of 18 S.W.G. wire is given by $R_n/R_0 = 1 + \frac{0 \cdot 131}{10^{10}} n^2$, whereas the theoretical formula for a single length of this size of wire is $R_n/R_0 = 1 + \frac{0 \cdot 16\, n^2}{10^{12}}$. The discrepancy between the observed and theoretical results is no doubt mainly due to the disturbance in the axial symmetry of the current distribution brought about by the close proximity of the return current, a condition of affairs that must exist in all stranded conductors.

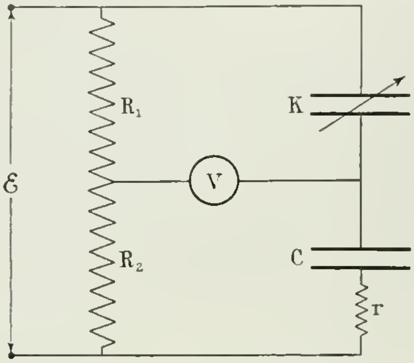


FIG. 16.

(*d*) *Measurement of amplification produced by triode amplifiers.*—The voltmeter is useful in constructing high-frequency amplifiers, for the amplification ratio can be directly measured. The grid type of instrument is most suitable for use with resistance amplifiers, for its reading will not be affected by the large, steady P.D. existing across the anode resistance. Fig. 15 shows the curve connecting input and output voltages (at $10^5$ p.p.s.) from a two-stage high-frequency amplifier, the valves used being of the "R" pattern with about 60 V on the anode.

(*e*) *Measurement of signal strengths in wireless telegraphy.**—By interposing a simple two-stage amplifier between the voltmeter and the aerial tuning coil, and without resorting to retro-action in the aerial, signal E.M.F.'s of 300 $\mu$V at $3 \times 10^5$ p.p.s. have been accurately measured, and signal E.M.F.'s of less than 50 $\mu$V have been detected.

(*f*) *Determination of the power factor of condensers.*—The power factor of a condenser can be determined in a very simple manner by using a grid-type voltmeter to measure the P.D. across the diagonal of a condenser bridge. The scheme of connections is shown in Fig. 16, where $R_1$ and $R_2$ represent equal non-inductive resistances, and K a variable air condenser which is assumed to have zero power factor. C represents the condenser to be tested, its imperfection being represented by the resistance r; $\mathcal{E}$ is a source of alternating E.M.F. of any required frequency, and V is the thermionic voltmeter.

If the power factor of condenser C is not zero, the P.D. across it will differ slightly in phase from the P.D. across $R_2$, and, even though K is adjusted so as to be equal in value to C, the voltmeter V will not read zero but a minimum. This minimum reading of V is equal to the vector difference between the P.D. across C and the P.D. across $R_2$. So long as this vector difference is small compared with $\mathcal{E}$, the ratio $2V/\mathcal{E}$ will measure the angle by which the phase of the current through the condensers departs from the ideal "quadphase" condition, or, in other words, the power factor of the condenser C. For a given reading of the voltmeter V, the smallest angle which can be measured depends simply on the value of $\mathcal{E}$. The smallest value that can be read with an accuracy of 5 per cent is about 0·5 V, so that the smallest measurable angle is about $1/\mathcal{E}$ radians, or, if $\mathcal{E}$ is 300 V, about 12 minutes of arc. The accuracy of the method has been tested by using an air condenser for C and inserting a known resistance for r; under these conditions $r\omega C/2$ should equal $2V/\mathcal{E}$.

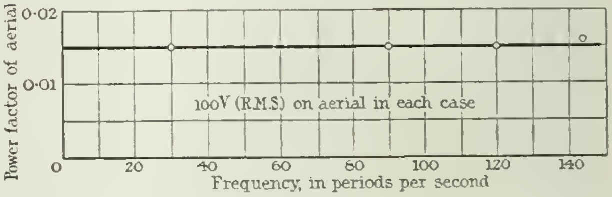


FIG. 17.

As an example of many such tests the following may be quoted for a case where $C = K = 5\,000\ \mu\mu$F, $r = 10\,000$ ohms and the periodicity = 90 p.p.s. The observed values of $V$ and $\mathcal{E}$ were 1·5 V and 212 V respectively, so that $2V/\mathcal{E} = 0 \cdot 0142$, whereas the calculated value of $r\omega C/2 = 0 \cdot 0141$. This method has been used to measure the power factor of an aerial, and incidentally it forms a convenient way of measuring the capacity of an aerial. Fig. 17 exhibits the power factor of the aerial at the Cambridge University Engineering Laboratory at frequencies ranging from 30 p.p.s. up to 150 p.p.s., the voltage on the aerial being 100 V in each case. It may be observed, in passing, that the power factor of the aerial is not entirely independent of the frequency, as Fig. 17 seems to show, but is appreciably different at frequencies of many thousands per second.

(*g*) *Measurement of stray magnetic fluxes.*—The thermionic voltmeter affords an ideal means of mapping stray alternating magnetic fields. The sensitivity of the instrument permits the search coil being of few turns and small linear dimensions, an important consideration where space is very restricted; moreover, as the instrument takes no current, the configurations of the fields to be investigated are not disturbed by the presence of the search coil. It is suggested that the method may be most useful for investigating the stray fluxes in transformers, or zig-zag leakages in induction motors, and other kindred problems.

---

* See also E. B. MOULLIN, "Observations on the Field Strength of Horsea Wireless Station," *Journal I.E.E.*, 1922, vol. 61, p. 67.

To illustrate the possibilities of the method some preliminary investigations have been made of the leakage fluxes occurring in a choking coil with a variable air-gap

The form and dimensions of the choking coil used are shown in Fig. 18. Magnetizing coils of 100 turns each were wound centrally on each limb and occupied a length of 3 inches; the cross-sectional area of the iron was 10·7 cm$^2$. Search coils, each having the same number of turns, were wound round the core at the points marked AA′, BB′, CC′ and DD′ respectively. Coil AA′ embraced sensibly all the flux threading the magnetizing coils, but would have been more advantageously placed centrally underneath one of the two magnetizing coils. Coil CC′ embraces the flux that issues from the end of the limb, and this is sensibly the same flux that actually crosses the gap and, passing through the head-piece, threads coil DD′. Coil BB placed ¾ inch further down the limb embraces more flux than coil CC′ by the amount which leaves the flanks of the limbs between coils BB′ and CC′. Coils AA′ and CC′, or coils AA′ and BB′, were joined in series but opposing, and the resultant E.M.F. produced in them was measured by the anode-type thermionic voltmeter. The voltmeter reading is consequently proportional to the difference between the fluxes threading the two coils or, in other words, the leakage flux between the two points. Since this leakage flux occurs through paths that are mainly air, it must be sensibly proportional to the current through the magnetizing windings.

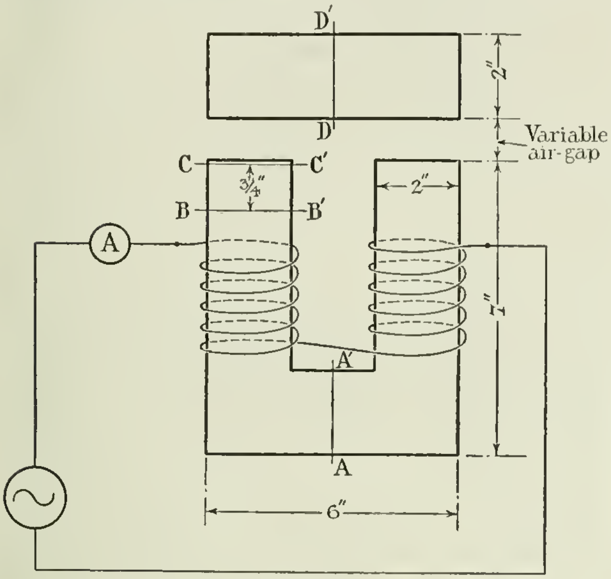


FIG. 18.

Fig. 19 relates to a test of the choking coil at a constant voltage, the current through the windings being altered by varying the length of the air-gap, the mean flux density inside the magnet windings being about 3 000 lines per cm$^2$ at time of maximum value. The percentage leakage of flux between AA′ and BB′, also between AA′ and CC′, is plotted against the R.M.S. current through the magnetizing windings. The result is seen in each case to be a straight line, but a line not passing through the origin. The reason why the line departs from the origin is probably because coil AA′ was not situated centrally under one of the magnetizing coils. Had this been the case the E.M.F. generated in coil AA′ would always have been a little greater, and so the difference between coils AA′ and CC′ would have been also a little greater. It will be noticed that the leakage flux appears to become zero when the current is 0·5 A. This is exactly the current taken by the choker with the gap closed up; and in this condition the search coils are situated almost symmetrically with respect to the flux and would therefore have equal E.M.F.'s in them, with or without a small amount of stray flux between them.

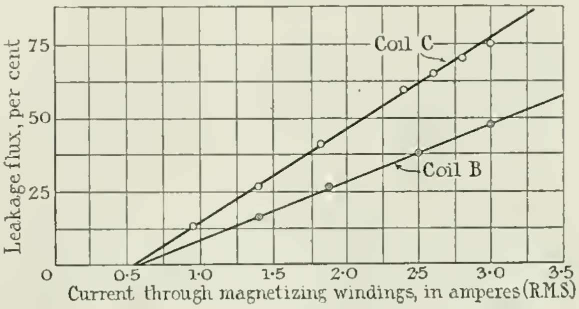


FIG. 19.

(*h*) *Miscellaneous uses.*—If the grid-type instrument is connected across a resistance placed in the field circuit of an alternator, it can be used to measure the extent of the small alternating current superposed on the steady field current, or it may be used to measure the voltage ripples of a d.c. dynamo. Both these applications depend on the fact that it is not cognizant of a steady potential. In this and similar applications it may prove a useful instrument for those who have constantly to diagnose faults in dynamo-electric machinery, and it would often serve to discover a fault that could otherwise have been found only by the help of an oscillograph or other delicate and unportable apparatus.

With the help of an amplifier it may be employed with a thermo-couple to measure the extent of cyclic variations of temperature, such as those occurring in an engine cylinder.

## DISCUSSION BEFORE THE WIRELESS SECTION, 6 DECEMBER, 1922.

**Professor C. L. Fortescue:** It may well be argued that all the principles involved in this instrument are well known, but it has remained to the author to realize the need for this voltmeter and to produce it in a practical and simple form; and for this he deserves full credit. Of the many applications mentioned in the paper the measurement of high-frequency resistance seems one of the most important, and it is possible that for this purpose the instrument may prove as useful to the wireless engineer as the testing set is to the "heavy" engineer. As a resonance indicator the voltmeter will, no doubt, operate fairly effectively, but this would not appear to be its strong point, and the ordinary "slide-back" method, using a good galvanometer and a strongly negative grid, is far more sensitive. There seems to be some reason to doubt whether the calibration will be permanent. Changes of the grid, filament and vacuum occur in the valves even when run with low filament currents, and only experience of many thousand hours of running will show whether the method of setting the zero will compensate for all these changes. Some degree of screening may also prove necessary when working on very high-frequency circuits.

**Major H. P. T. Lefroy:** I feel that the instrument described in the paper is probably, at the stage we have now reached in high-frequency engineering, about the most useful one that has been produced for a considerable time, and that its use may lead to improvements in radio apparatus in almost every direction. More particularly, it will enable us to gain a valuable insight into the design of high-frequency conductors and coils, and on various other points which have been difficult to investigate on account of the difficulty of measuring very small high-frequency currents. The instrument is one, moreover, which amateurs can easily obtain, so that, if they wish, they can join in some useful and effective research work. For instance, they are now in a position, with the help of this instrument, to measure signal strength accurately, and to join in the international investigation of signal strength in a way they could not before. In the early part of the paper it seems to me that the author rather suggests that all balance methods are too cumbersome; but in similar work which I have done, using simply a 2-volt accumulator and a 10 000-ohm resistance-box, I was able easily to balance to an accuracy of $0 \cdot 1$ $\mu$A, and then to get readings, from signals, up to 1 000 $\mu$A, which is a very wide range. I think that high-frequency voltages down to $0 \cdot 01$ volt can thus be measured, simply by putting the accumulator current differentially through the micro-ammeter relative to the anode current. In my experiments I noticed an interesting point, viz. that signals which reduced the anode current by 20 $\mu$A were about R9 in the telephone, while those causing a reduction of 500 $\mu$A were only R10 or R11, and those about R6 did not cause a reduction of 1 $\mu$A.

**Dr. E. H. Rayner:** There are one or two points which I should like to raise. Has the voltmeter to be calibrated for each particular valve, or is it sufficient to take a given type of valve and substitute one for another? I ask that because for a certain purpose some work has been done recently on valve characteristics, and it was impossible to find two valves with exactly the same characteristics, although they might be of the same manufacture. Another point is this: I notice that the terminals for the connection to the voltmeter are put almost as far apart as possible, but it seems to me that in order to reduce the inductivity of the circuit, with the stray fields which may be present, it would be desirable to bring them closer together, as is usually done in apparatus for very high-frequency work.

**Mr. J. Hollingworth:** To take a measurement in wireless work often requires far more apparatus than is in use for the whole of the rest of the experiment, and the advantages of a portable instrument are therefore very great indeed. I think we might even go so far as to say that even if the instrument were not found to be an instrument of precision—I do not suggest for one moment that it is not—its value to the alternating-current worker would still be very great. Some time ago when I was trying to use a constant oscillating circuit I adopted the method of always resetting the filament current so as to obtain the same anode current with the same anode voltage, the idea being that it was much more sensitive to anode current, and anode current can be adjusted much more accurately than filament current can be. On calibrating it after three months I found that it had changed 30 per cent. Whether I had a particularly bad valve or not I do not know, but as a result of that I connected up the circuit with a measuring instrument in series, left it on and watched it hour by hour. There were even slight changes during that period, so I think that it will be necessary to make sure that the right point on the anode characteristic is being worked to, unless it can be shown that small variations of the anode characteristic do not produce any appreciable effect. I should like to ask if, by the addition of various resistances in the position occupied by R in Fig. 4, the instrument could be converted into a multi-range apparatus, so extending its uses. I think that the power absorption of the voltmeter varies slightly with the power applied to it; in fact, the apparent resistance of the voltmeter appears to vary slightly with the reading. That, of course, introduces the difficulty that if one is using it on an oscillating circuit, where decrement is of importance, and where the decrement of the voltmeter is comparable with that of the circuit, one does not know the decrement of the circuit until one knows the reading of the voltmeter. If the voltmeter is equivalent to a constant resistance, that will not matter, but if the equivalent resistance of the voltmeter varies with the reading it means recalculating for each reading in order to determine the actual decrement of the circuit.

**Mr. F. C. Lunnon:** The author's voltmeter is essentially a calibrated apparatus and I think that he rather underestimates the difficulty of obtaining a calibration, for surely it will depend upon the wave-form of the voltages to be measured. I notice that he rather lightly passes over what has come to be known as the "slide-back" method of measurement. In working under Capt. Round I have used this method for various purposes for a number of years and if it is employed with a knowledge of its error it is sufficiently accurate for most radio measurements. It is essentially not a method for measuring such low voltages as those for which the author's instruments are calibrated, for the reason—which we have always appreciated—that there is a small, constant error inherent to the method, depending on the type of valve used, which would result in too big a percentage error at these small values. About a year ago I made extensive checks on this method at low frequencies, trying a large number of valves of different types. The result showed that for any particular type of valve the error is practically constant from valve to valve and over a large range of voltage and so, of course, the percentage error decreases as the voltage to be measured increases. For instance, using a M.-O. dull emitter valve the error is 0·2 volt low, which represents a 4 per cent error at 5 volts. A M.-O. V24 valve gives a bigger error, viz. 0·4 volt low. If care is taken to use valves with a good, sharp cut-off—such as a dull emitter—the error will not be greater than 4 per cent for voltages of over 5 volts, and over 10 volts it will be very small indeed. And if, when using a dull emitter, 0·2 volt is added to the readings then, over about 6 volts, the error can be relied upon to be less than 1 per cent. Figs. A and B illustrate these results, and Fig. C and Table A give the results of high-frequency checks which were made three years ago. A point in favour of the "slide-back" method is that the very principle by which it operates ensures that no damping can be introduced into the circuit to which it may be connected; and a still greater point in its favour is that it is definitely a measure of peak voltage as against R.M.S. voltage—necessarily doubtful because it depends on wave-form—such as is obtained with the author's voltmeter. He suggested that his voltmeter could be used to measure signal strength by measuring the voltage across an aerial tuning inductance and then calculating the induced E.M.F. in the aerial from a knowledge of the inductance, frequency and resistance of the aerial, and he remarked that this would be a simple method and one that might supersede the present complicated aural method—presumably that

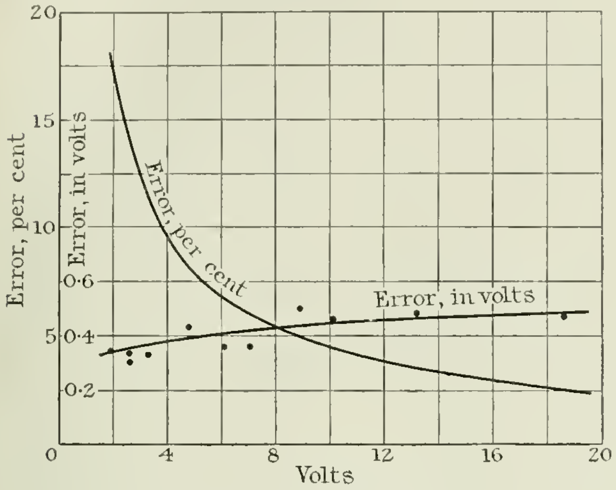


FIG A.—Curves of error of a V24 valve (No. 21 288). 4 volts across filament; 12 volts on plate.

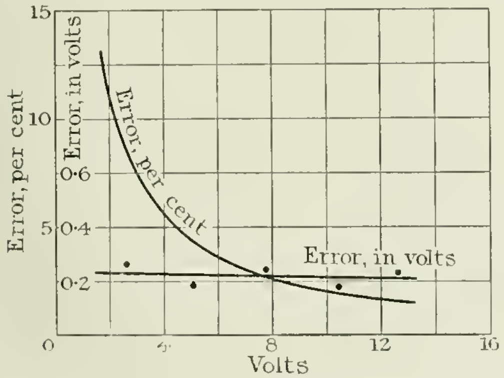


FIG. B.—Curves of error of an S.M. valve (dull emitter) No. 235. 2·18 volts across filament; 7 volts on plate.

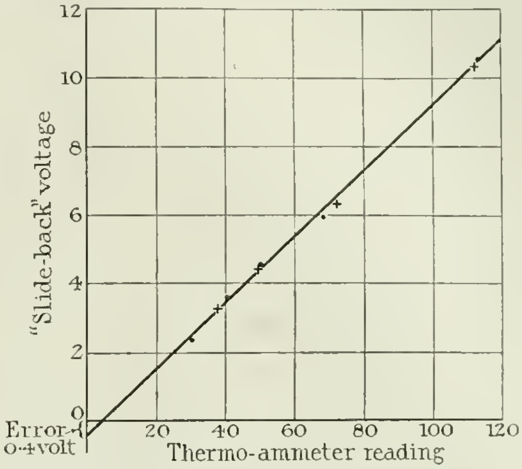


FIG. C.—Test for proportionality between current in an oscillatory circuit and resulting voltage across condenser as measured by the "slide-back" method. V24 valve.

TABLE A.

*V24 Valve.*

Peak voltage measured by the "slide-back" method across an inductance $L = 1\,460\,\mu$H at $\lambda = 6\,050$ m and compared with the calculated voltage determined from the current $I$ as measured by a thermo-ammeter.

| "Slide-back" voltage | Calculated voltage | Percentage error |
|---|---|---|
| 15·2 | 15·3 | 0·655 |
| 26·1 | 26·2 | 0·38 |
| 23·7 | 24·1 | 1·66 |

used by the Marconi Company and described by me in the discussion on "Long-distance Wireless Transmission" before this Section in 1921.* This might be so under ideal conditions—with the stations to be measured sending a long dash and in a complete absence of interference from atmospherics or other stations—but it is most certainly not so for practical signal-strength measurement, for example, measuring New Brunswick in England, where the current in the aerial resulting from the E.M.F. induced by the New Brunswick signal is far weaker than the forced current from nearby high-power stations on slightly different wave-lengths, viz. Carnarvon and St. Assise, and far weaker also than the current resulting from atmospherics. And when, in addition, it is remembered that in practice stations send Morse signals and not long dashes it must be obvious that only an aural method, such as that referred to above, can give any results at all.

**Major B. Binyon:** It is well known that valve filaments are very liable to fracture in transit and, in view of the fact that the calibration of this instrument depends upon the particular valve employed, it would presumably be necessary to return the instrument to the makers for re-calibration in the event of damage to the valve. I should like to ask the author whether he has considered the employment of any special type of valve to overcome these difficulties and whether it would not be possible to employ a valve having a very thick tungsten filament with a current of, say, 3 or 4 amperes or more, which would give an exceedingly long life and not be liable to damage in transit. Since the instrument is not required for continuous use a high filament current would be immaterial.

**Mr. R. C. Clinker:** I think that anyone who has made alternating-current measurements, particularly measurements of small voltages, will often have felt the need of an instrument such as the author has described. It would be very useful, for instance, in measuring the permeability of iron under a.c. conditions at very low density where a low voltage is induced in a search coil. On page 301 the author mentions the measurement of current by noting the frequency and passing the current through a known inductance. For that, I suggest, it is necessary not only to know the frequency accurately, but also to be sure that the wave is sinusoidal, i.e. that no harmonics are present, which I think is more difficult. I should like to know if the arrangement shown in Fig. 16 would give as good or better results if a variable resistance were put in series with the condenser K and varied until V gave a zero reading. The power factor of the arm containing condenser K would then be known and would be exactly equal to that containing condenser C and resistance r.

**Dr. E. V. Appleton** (*communicated*): I think that the voltmeter designed by the author (see Fig. 3) will play a great part in the signal measurements of the future. We have had an opportunity of using this type of voltmeter in the Cavendish Laboratory, and have found it quite accurate and very convenient. At first I thought that all the author had done for us was to put a triode in a box, bringing out connections to convenient terminals, but a closer acquaintance with the difficulties of the problem make us admire the way in which he has made the calibration independent of fluctuations of filament-battery voltage. I have been personally interested in two applications of the voltmeter, both relating to the measurement of the strength of continuous-wave signals. For very strong signals, such as are used in measuring the effective heights of aerials, a loop aerial may be used, and the resonance voltage across the condenser may be measured by means of the voltmeter. The insertion of a small, known non-inductive resistance in the coil circuit alters the resonance voltage reading so that from the two values the oscillatory-circuit resistance may be found. The calculation of the signal electromotive force is then a simple matter. In the second method the signal strength is measured by means of the "silent space" which it produces in a simple auto-heterodyne receiver. Thus, if the edge of the "silent space" corresponds to a dis-tuning $\delta\lambda$, where $\lambda$ is the wave-length, the signal electromotive force $E_0$ is given by $E_0 = K(\delta\lambda/\lambda)a_0$, where $K$ is a known constant and $a_0$ is the oscillatory amplitude of the receiver in the absence of signals. Since $a_0$ may be made of the order of 0·5 volt it is conveniently measured by the author's voltmeter. I know of no other instrument which would be as suitable for such a purpose.

**Mr. E. B. Moullin** (*in reply*): Prof. Fortescue and Mr. Hollingworth have suggested that the calibration may not remain permanent over a long duration of time, but whether this will prove to be the case or not experience alone can show. If the filament voltage is kept down to 3·6 V I hope and expect that no appreciable ageing will take place. I have had one of these instruments in constant use for about 8 months and no change has so far taken place in the calibration: it is extremely easy to make a low-frequency check of the calibration, and until long experience has been gained it may be as well to check the instrument every 6 months or so. It is possible that ageing effects would be equivalent to a very small change in filament potential, and experiment shows that such small changes affect only the zero and not the law of the scale. Hence if ageing does take place it is quite possible that the instrument can be corrected by slightly setting up the pointer zero without making any alterations in the scale.

Prof. Fortescue and Major Lefroy have referred to the use of the instrument for measuring high-frequency resistances. I have used it a great deal for measuring aerial resistances and coil resistances by employing it as a current indicator, while the E.M.F. introduced into the circuit was measured by a potentiometer slide-wire.

In reply to Dr. Rayner each instrument has to be calibrated with its own particular valve, but in the case of the grid instrument different valves by the same manufacturer seem to repeat themselves within 5 per cent.

As Major Binyon suggests, it may well be advantageous to use a thick filament and so avoid all risk of damage in transit: this might also permit of a slightly less sensitive galvanometer being employed.

I am afraid that the amount of scale control obtainable by altering the anode-circuit resistance is not sufficient to provide a multi-ranging device, but no doubt a considerable extension of scale could be provided in this manner.

---

* *Journal I.E.E.*, 1921, vol. 59, p. 677.

The method of calculating the effective resistance of the voltmeter at any reading is set out in the paper, and I think that the example given at the end of Section 4 is a fair one for the purpose of showing that there are few cases where the decrement will be of importance. If cases arise where the decrement is important it is only necessary to tap the voltmeter across a portion instead of the whole of the inductance, and thereby reduce the decrement introduced; this, of course, means an increase in the power supplied to the circuit, but the sensitivity of the instrument when used as a current indicator is so great that this is of no practical inconvenience.

Mr. Clinker's suggestion of placing an extra resistance in the condenser arm of the bridge and so producing a balance would usually be an improvement: with very small condensers and low frequencies this added resistance would have an inconveniently high value.

I agree with Mr. Lunnon that the calibration must be to some extent dependent on wave-form, but to what extent has not so far been investigated. In high-frequency work where one is usually working with highly inductive circuits of low decrement tuned to resonance it does not seem possible that one can get harmonics in the current that are comparable with the fundamental, hence I think that no anxiety as to wave-form need be felt in high-frequency work. I do not see how the slide-back method is any better in this respect, for the peak voltage which it measures is also dependent on wave-form. Also, a reference to my analysis of the accuracy of the slide-back method which recently appeared in the *Wireless World* (1922, vol. 10, p. 1) will, I think, show that Mr. Lunnon's constant correction of about 0·4 V will depend very much on the wave-form. I think he will agree that if the wave had a dimple in the top, and, therefore, two peaks, the constant correction would be much less than 0·4 V, and that if it had a very sharp peak instead of a dimple, the constant correction would be much more than 0·4 V. Another disadvantage that the slide-back method appears to possess is that not only is it necessary to add a rather uncertain correction but there must also be some uncertainty in deciding on the appropriate slide-back. That this uncertainty does exist is clearly shown in Mr. Lunnon's curves, in which the observation points are scattered above and below the line. Above, say, 15 V the method may no doubt be taken as correct, but this makes the slide-back 10 times as insensitive as the instrument described in the paper.

The aural-comparison method to which I referred was the method described by Prof. Vallauri and is probably similar to that used by Mr. Lunnon. I have used the voltmeter a good deal for measuring signal strengths, and according to the Austin-Cohen formula it is quite possible to measure transatlantic signals by the method indicated in the paper and recently described more fully in the *Journal*.*

---

* *Journal I.E.E.*, 1922, vol. 61, p. 67.

# DISCUSSION ON

# "OBSERVATIONS OF THE FIELD STRENGTH OF HORSEA WIRELESS STATION." *

**Mr. J. Hollingworth** (*communicated*): The experiments and results given in the paper are very interesting to those who are engaged on this problem of measurement. It is to be noted that the author confirms the present general tendency to avoid the use of an audible system wherever possible, though there may occasionally be cases in which it is preferable. A certain number of measurements were made at the National Physical Laboratory on this transmission, but their object was largely to investigate a new system of measurement. Time did not allow of this being calibrated before the tests commenced, so that readings were discontinued after a time in order that it might be done, with a result that on no occasion did the date of Mr. Moullin's tests coincide with those at the N.P.L., so that direct comparison is not possible. I should like to express my absolute agreement with the author where he emphasizes the necessity of check measurements. In such an indirect process as a measurement of this type the possibilities of something going wrong are so great that it is very difficult to place entire reliance on a single reading unsupported by any internal evidence. With regard to details of the system, the discrepancies in the results obtained with the different mutual inductances are very likely due to a small capacity coupling. Personally, when using a similar system I never rely on a calculated value, but proceed as follows: The larger mutual inductances can be measured directly by passing a rather larger current at the given frequency through the primary and connecting a Duddell thermo-galvanometer across the secondary. Provided one is not working near the natural wave-length of either coil, the mutual inductance can be calculated from these figures and the low-frequency inductance of the secondary. This process breaks down for the smaller values of mutual inductance, but by measuring the same signal with different pairs of mutual inductances a ratio $M_1 : M_2 : M_3 \ldots$ can be obtained. I have found that over the range in which both methods of measurement are possible the ratios obtained by the two methods are almost invariably within 1 per cent of one another, and so I have no hesitation in accepting the ratio obtained by the second method for mutual inductances which are too small to be measured by the first. Hence, if the absolute value of the largest mutual inductance can be measured by some direct method, the values of all the others can be found. There appears to be considerable difference of opinion over the meaning of the effective height of an aerial as used in the formula

$$E = \frac{K\pi h_s I_s}{\lambda d}$$

At the Paris Conference, 1921, it was suggested that it should be defined as the height of the equivalent half dipole, and the constant $K$ is then 120. It was also suggested that, as a first approximation, the effective height should be taken as 0·55 of the mechanical height; and in the *Radio Review* of April 1921 Prof. Vallauri gives this ratio for the Rome aerial under certain conditions as 0·64. Hence in Mr. Moullin's formula where $K = 60$ is used, it appears as if his value of the effective height should at times exceed the actual height, which appears to contradict his remarks in the second column of page 72. As a matter of fact, in the N.P.L. measurements $K$ was taken as 120 and $h_s$ as 100 (this value being assumed, as the correct value was unknown). The results on the 2 500-m signals mostly came out about 10 to 20 per cent in excess of the theoretical value, neglecting absorption. It appears, therefore, that if the correct value for $h_s$ had been used, the results would have shown the absorption between Horsea and the N.P.L. to be negligible.

**Mr. E. B. Moullin** (*in reply*): I agree with Mr. Hollingworth that it is very advisable to make an actual measurement of the mutual inductances, but, as mentioned in the paper, adequate means for doing so were not at my disposal. Personally, I much prefer to measure the local E.M.F. by means of a resistance potentiometer, because by so doing it is much more easy to make calibration curves of the type shown in Figs. 7 and 8. If the resistances are made of short lengths of fine wire doubled back on themselves I think that there is no need to fear that the potentiometer has a reactance comparable with its resistance, at any rate for frequencies less than $10^5$ periods per second. In any case, as the reactive drop is at right angles to the resistance drop it can have an appreciable value and still make only a second-order change in the total drop.

I am glad that Mr. Hollingworth has called attention to the discrepancy that exists in defining the effective height from the formula $E = K\pi h_s I_s/\lambda d$, for it seems to me that this discrepancy is bound to lead to confusion in the future; it seems common to find $K$ taken as 60, and equally common to find it taken as 120. Now it seems to me to matter very little which value of the constant is taken so long as everyone takes the same. Would it not be a good thing to have some definite ruling on this point, together with some rules as to the manner in which the effective height is to be measured? If this were done then we should know that all values quoted for the effective height of an aerial were defined and measured in a standard way.

With regard to the effective receiving height measured as described on page 72, surely this method of measurement is independent of the value of the constant discussed above. The value of the field strength produced by a distant station is first measured by means of a loop, and it is then found that the same field produces a certain E.M.F. in an aerial. In the case of an aerial where capacity is sensibly all concentrated in the roof, the value of the E.M.F. divided by the field strength must surely give the effective receiving height. In the particular case considered, the curve showing the current distribution in the up lead proves that the capacity was concentrated in the roof.

---

* Paper by Mr. E. B. Moullin (see page 67).

# INTRODUCTORY NOTES TO A LECTURE ON
# "VARIABLE-SPEED ALTERNATING-CURRENT MOTORS WITHOUT COMMUTATORS."

By F. Creedy, Associate Member.

(*MS. first received 23rd November, 1922, and in final form 7th March, 1923; lecture delivered before* The Institution *4th January, before the* North Midland Centre *9th January, before the* South Midland Centre *10th January, and before the* North-Eastern Centre *22nd January, 1923.*)

## Summary.

After a short general discussion, a new method of pole-changing, involving the use of a number of phases greater than that in the line, is explained, together with means for simplifying the connections:—

(A) By the use of mutually reversed coils.
(B) By a star-mesh connection.

The phase transformer needed to produce the increased number of phases is next described, and it is shown that the current in the windings intermediate between the three-phase tapping points is reduced to a very low value as in the rotary converter, making the apparatus small and inexpensive.

The switchgear employed is next discussed, and it is pointed out that the methods described render the squirrel-cage motor adaptable to almost all purposes, since they enable it to give good starting torque with low current.

Machines with slip-ring characteristics are also described and test-results discussed.

A description is given of the cascade motor, and its unique characteristic of giving gradual adjustment between speeds is explained. Two-, three- and four-speed motors having this characteristic are referred to.

Some tests of large rolling-mill and other motors are given and finally a description of the application of the cascade motor as a short-circuit motor machine with slip-ring characteristics, and as a unity-power-factor synchronous machine of greater simplicity and less cost than any other type.

## Introduction.

It has become sufficiently clear during the past few years that the polyphase alternating-current system will ultimately be universally adopted for power supply on a large scale. One of the chief difficulties at present existing with this system relates to the provision of a satisfactory variable-speed motor, capable, if possible, of operating on high-tension polyphase currents without the necessity for the transformation of the whole of the power. The solution of this problem is very far from being an easy one and, in fact, it is only in comparatively recent years that satisfactory progress has been made.

In the first place, the different applications for a variable-speed motor vary very widely among themselves, and it is by no means likely that a single type of motor is best adapted to meet the whole of these different forms of application.

It will be desirable first of all, therefore, to consider rather more in detail what is the real nature of the problem of producing a satisfactory variable-speed alternating-current motor to meet every kind of practical condition.

## The Problem of Variable-speed Alternating-current Motors.

There are, in fact, a considerable number of different classes of variable-speed service.

These may be more or less accurately summarized as follows:—

(1) *Speed-range.*—All practical applications, with very few exceptions, can be covered by a motor having a speed-range of 3—1. Other speed-ranges in wide demand are 2—1 and 1·5—1. It would, of course, be desirable, if compatible with the other conditions of the problem, to have a machine capable of gradual speed-variation from one end to the other of any of these ranges without continuous loss of power at any speed. If this should not prove possible, and it becomes necessary to use a number of speed steps, these should be fairly numerous, say not less than 4 to 6, in a speed-range of 3—1.

(2) *Starting.*—In certain cases, e.g. the compressor drive, the printing press or the reciprocating pump, variable-speed motors must be capable of starting with a very high torque, while others, e.g. machine tools and fans, require only a moderate starting torque, hence provision must be made for both these cases.

(3) *Speed changing.*—In certain cases, e.g. machine tools, printing press drives, compressors, lifts and cranes, etc., the speed has to be changed while running; while again in others, e.g. mine fans, pumps, calenders and merchant mills, the speed is only changed occasionally in changing operations, though here, of course, the speed-variation required in order to render the use of a flywheel possible is not referred to, but merely that required to enable the mill to deal with different classes of work.

In these cases there is no serious objection to shutting the machine down and re-starting, and where this is possible the problem is simplified to a considerable extent.

Where the change of speeds is in steps, care must be taken that the change from one step to the next is effected without a serious shock to the system, either mechanical or electrical.

(4) The first cost of the equipment, as well as the cost of attendance and upkeep, must be moderate. Repairs must be capable of being carried out without difficulty.

(5) The efficiency of the equipment should be as

high as possible, since high efficiency over a large range of speeds is the chief object of installing a variable-speed alternating-current motor. A low consumption of wattless current is also desirable.

(6) For the vast majority of applications the motor should be capable of giving a constant torque at all speeds or a horse-power proportional to the speed. For a certain class of machine tools, however, a constant horse-power characteristic is desirable.

The object of speed-variation in the driving of machine tools is to enable a cut to be taken on different diameters at the same peripheral speed, objects of large diameters being driven at a low speed (r.p.m.), and objects of a small diameter at a higher speed. Where, as in lathes, modern drilling machines, milling machines, etc., the amount of energy dissipated in friction is small and most of the power of the drive is actually devoted to cutting, this means that approximately the same horse-power is taken by the tool at no matter what speed it operates.

There is, however, another class of tool in which the size and weight of the tool is determined chiefly by the necessity of rigidity, e.g. large boring mills, planers, etc. In this case the greater part of the energy supplied to the tool is devoted to the moving of heavy masses and is ultimately dissipated in friction. In this case the tool requires a constant torque and an amount of power in proportion to the speed.

### Difficulties in Designing a Satisfactory Variable-speed Alternating-current Motor.

The most obvious way to produce such a motor is to make the closest possible imitation of the direct-current machine, and it has long ago been shown that numerous types of single-phase and polyphase commutator machines having, in theory, characteristics resembling very closely those of the direct-current machine are possible. These commutator machines have never been more clearly described than in a lecture * given by Dr. S. P. Smith, but it is indisputable that the present wide utilization of electric power supply is due very largely to the simplicity and robustness of the polyphase induction motor and I have always thought it a disastrous mistake to abandon the induction motor without examining whether some system of control cannot be worked out so as to enable it to carry out satisfactorily without any fundamental alteration variable-speed requirements.

Every variable-speed application should, in my opinion, be considered on its merits. In some cases a commutator machine is undoubtedly the right apparatus to use. Its advantages are the greatest :

(1) On constant-speed work where it is possible to keep the size of the commutator and the amount of brushgear within reasonable limits by appropriate design.

(2) On very low-frequency circuits where similar possibilities exist.

(3) Where there is an imperative demand for a continuously adjustable speed justifying all the sacrifices in other directions which must be endured in order to attain it. These cases are, however, in my opinion, relatively few. Assume, for instance, that we wish to drive a boring mill by means of a variable-speed alternating-current motor, the best speed of the table for a particular class of work being 20 r.p.m. With a speed control by steps it may be impossible to get exactly this speed, speeds of 19 r.p.m. or 21 r.p.m. being the nearest available, and I feel that this difference is not worth considering in most cases.

Confining ourselves therefore to methods of controlling the induction motor so as to obtain variable-speed shunt characteristics, we find that its natural lines of development are two in number :—

(1) Speed change by changing the number of poles.

(2) Speed change by cascade operation.

Both these methods lead to extremely useful types of apparatus and I propose to discuss each in turn.

## Part 1.

### Speed Change by changing the Number of Poles.

Without ignoring the work of early inventors, such as Dahlander, Lindström and Alexanderson, who have provided means of adapting a single winding to give, for instance, two numbers of poles having a fixed ratio, it is not unfair to say that the idea of using the method of pole changing to produce a machine having anything resembling a gradual variation of speed by small steps between wide limits, would have been regarded a few years ago as chimerical. Yet it is also obvious that if by any means we could render practically available all the numbers of poles which exist within a given range, we have a machine with a very high degree of practical usefulness. For instance, on 50 periods between the speeds of 375 r.p.m. and 1 000 r.p.m. there are six numbers of poles available.

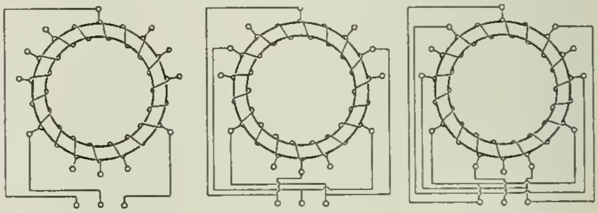


Fig. 1.

As the methods by which all these numbers of poles are rendered practically available have not yet been publicly described, I propose to dwell on them at somewhat greater length than is devoted to the methods of speed-variation previously described.

One method by which all these numbers of poles might theoretically be rendered available with a single winding has long been known, i.e. the use of a ring winding tapped at the various points necessary to give different numbers of poles, as shown in Fig. 1. It is well known that a ring winding can be used on any number of poles, if a number of equidistant tappings equal to three times the number of pairs of poles are brought out on each speed, equalizer connections being made between tappings 1 to 4 throughout the circumference. To obtain

---

* *Journal I.E.E.*, 1922, vol. 60, p. 308.

six numbers of poles from the same winding in this way, however, would require a formidable number of tappings, and to connect them together in the various manners required would involve an equally formidable type of switchgear.

In addition to this, the ring-wound machine is highly inconvenient from a manufacturing standpoint, though practically equivalent results could, in fact, be obtained from a lap-wound drum winding.

A further difficulty arises from the fact that the voltage induced in any section of the machine consisting of, say, two, three or more coils connected in series having a given number of turns is proportional to the rate at which the magnetic lines cut the conductors, and this rate is, of course, proportional to the speed of the flux wave, which is practically the same as that of the revolving element. Consequently, at the highest speed of the motor, the flux wave is cutting the conductors at a very high rate and, if the E.M.F. applied to any section is fixed, only a small flux will be required to produce it, owing to the high rate of cutting.

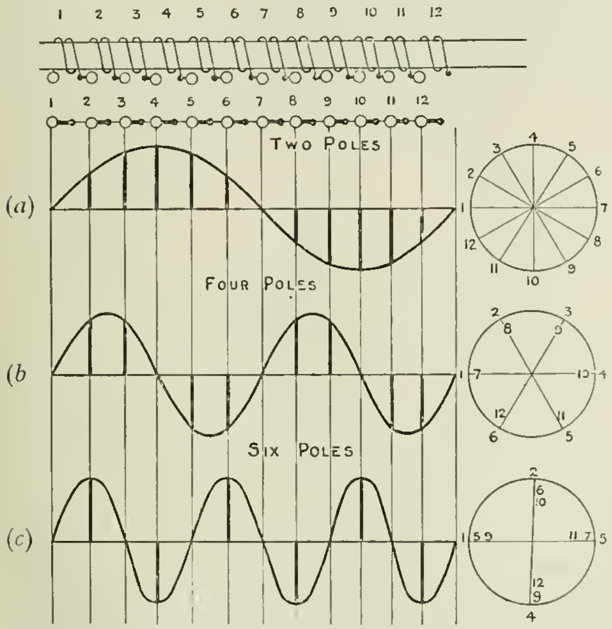


Fig. 2.

On the low speed of the motor, on the contrary, the flux wave is cutting the conductors at a low rate and, consequently, if the E.M.F. across the sections remains the same as before, a large flux will be necessary to produce it.

Hence, the flux of the motor will tend automatically to fall off in proportion to the rise of the speed in much the same way as it does in the direct-current motor, and hence such a motor having a constant voltage per section will tend to have a constant horse-power characteristic, which is not at all what is demanded in practice.

Means must therefore be provided to increase the voltage across each section more or less in proportion to the speed. These difficulties may be summarized as follows :—

(1) The difficulty of producing a winding having a moderate number of terminals and capable of simple switching.

(2) The difficulty of varying the voltage across a section containing a fixed number of turns, so as to keep the flux approximately constant with increasing speed without the use of costly apparatus.

*Method of overcoming these difficulties.*—The solution to all these difficulties was only found gradually. In order to overcome the necessity for a very large number of terminals, a method of pole changing entirely different from that described above was adopted. This method is shown in Figs. 2 and 3. Still considering a ring-wound machine, assume it to be divided into 12 sections, shown developed in Fig. 2.

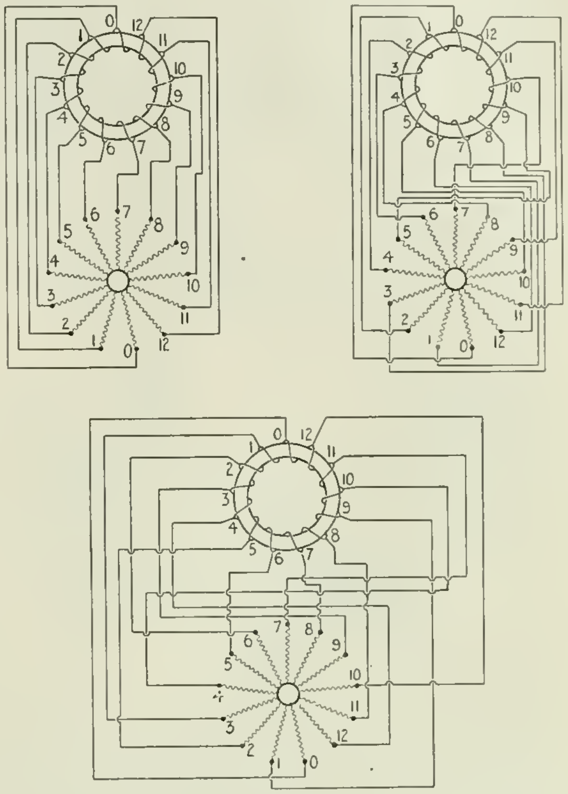


Fig. 3.

At this point it may be convenient to describe a diagrammatic method of denoting the windings of alternating-current machines which I have developed in order to simplify winding diagrams. It will be seen that the ring winding shown at the top of Fig. 2 is divided into 12 sections, each section being shown as consisting of two turns. The beginning of each section is denoted by a white circle and the end by a smaller blackened circle, the extremities of the various sections being connected in series in the usual manner. An obvious simplification for diagrammatic purposes is to omit the drawing of the winding and merely retain the two terminals of each section, joining them by a straight line in order to show that they belong to the same section. This diagrammatic method of denoting the winding is shown immediately below the drawing of the ring in Fig. 2, the sections being numbered in order round the circumference, and the method is made considerable use of in these notes.

Imagine the 12 sections of the ring winding shown in Fig. 2 to be carrying currents differing in phase from one another by 60°, the current vectors being shown on the right of Fig. 2 (*b*), the current in section 1 having a phase 0°, that in section 2 having a phase 60°, that in section 3, 120°, and so on. These vectors when projected on a vertical axis in the usual way give, of course, the instantaneous currents in the different sections, which may be plotted as shown on the left of Fig. 2 (*b*). We thus obtain a series of ordinates the extremities of which lie on a sine curve, having two positive and two negative maxima, i.e. four poles on the circumference. If, however, we so reconnect these sections that the phase difference between adjacent sections is 30° and plot out the ordinates as in Fig. 2 (*a*), we obtain another sine curve having one positive and one negative maximum, i.e. two poles, while if we make the phase difference between the sections 90°, as in Fig. 2 (*c*), we obtain a curve having three positive and three negative maxima, i.e. six poles.

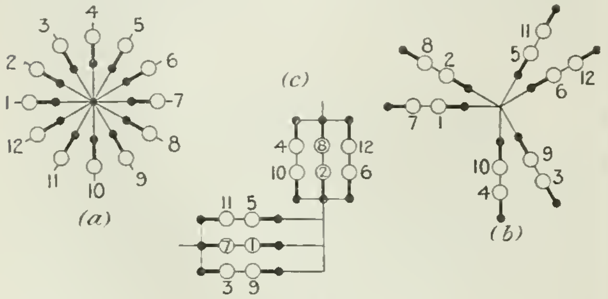


FIG. 4.

In Fig. 3 are shown the connections whereby this change of phases may be accomplished for the case of 13 phases, which is practically more convenient in some respects. As will be seen, it involves the use of 13 terminals on the motor (still shown as a ring winding) and some means of producing a number of phases (viz. 13) equal to the number of sections in the motor winding. Since thirteen-phase distribution is never used, this involves some means of converting from the usual three-phase supply to the number of phases required by the motor and a new piece of apparatus, the phase transformer or converter, is required with this method of control.

When we realize that this method of control involves a phase converter, it may appear as if we had merely simplified the switching by introducing another piece of apparatus which will cost as much as the switchgear with which we have dispensed.

It will be shown later, however, that this is far from being the case. The construction of this phase transformer with a suitable degree of simplicity involves problems of its own, particularly where a large number of phases are required. The method of solving these problems will be described at a later stage.

Although the simple method of pole changing just described was sufficiently encouraging to justify the construction of one or two machines for special purposes, it was not found sufficiently simple to be the final solution of the problem. Experience showed that even the number of terminals possessed by such a motor was too great in practice if a large number of speeds, e.g. five or six, was aimed at. In this case the number of terminals is not less than 30, which was found to be not a practical number, and still further means of simplification were therefore sought.

It was found possible to reduce the required number of terminals in several ways. It is clear, first, that wherever we have currents differing 180° in phase, that is to say, mutually reversed, it is not necessary to supply two distinct phase-transformer terminals to obtain these two phases. If the two sections are connected in series or parallel, mutually reversed, they can be supplied from a single terminal.

For instance, returning to Fig. 2, if we wish to connect the motor only for two poles and six poles we find that in both these cases sections 1 and 7, 2 and 8, etc., are diametrically opposite in phase. We may therefore connect them in series reversed as shown in Fig. 4 (*b*), in which the sections are denoted by the diagrammatic method already described and the direction of the straight line joining the two extremities is made to represent the phase of the current in the section.

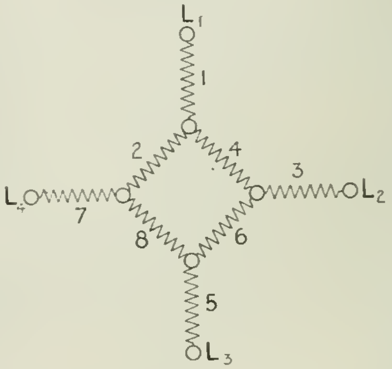


FIG. 5.

Connecting all the sections in star, we require 12 terminals to give two poles. Connecting opposite sections in series reversed we require only six, although if we compare Figs. 4 (*a*) and 4 (*b*), we see that each section in the latter is parallel to the same section in the former, i.e. it carries current of the same phase.

The same connection (viz. diametrically opposite sections connected in series reversed) is also available on six poles, and the diagram for this is shown in Fig. 4 (*c*). Hence, we see how by making use of this simple device we may materially reduce both the amount of switching and the number of terminals required on the phase transformer.

A second method of reducing the number of terminals consists in putting alternate sections of the winding in mesh and the remainder in star, the mesh being connected in the centre of the star as shown in Fig. 5, for the case of 8 sections and 4 phases.

It will be seen from this figure that the mesh sections are intermediate in phase between the star sections, e.g. section 2 is intermediate in phase between sections 1 and 3, and so on, thus, although the winding connected as in Fig. 5 requires only four terminals, the E.M.F.'s across the various sections are nevertheless in eight distinct phases.

Again, it was found in most cases that while this method of connection might suffice to double the number of phases on a particular number of poles, yet in order to produce the same result on another number, the whole or many of the sections must be disconnected from one another and reconnected in a different order. Thus it would seem that we have only simplified the transformation in order to complicate the switching.

The method of reversal and the star-mesh method may be combined, and thus we may obtain windings in which the E.M.F. across the sections has four times as many phases as that supplied to the terminals.

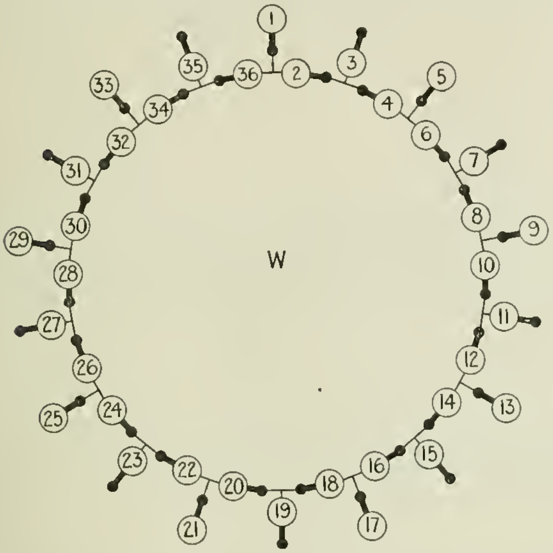


Fig. 6.

After a very large amount of research, extending over a considerable period of time, a winding was found in which this result could be accomplished, not on one number of poles only, but over a large series of numbers covering a speed range of 3—1 or more, without reconnecting the winding in any way when changing the numbers of poles. This winding is shown in Fig. 6 for the case of 36 sections, 18 of which are connected in mesh and an equal number connected in star to the angles of the mesh, alternate sections in the mesh being mutually reversed and alternate sections in the star being also mutually reversed, the mesh sections alternating with the star sections around the circumference of the machine.

The winding shown in Fig. 6 (containing only 18 terminals) can be, and is being, frequently used on all numbers of poles from 6 to 16 and is, with a slight further modification, also capable of being used on further numbers of poles from 20 to 26.

This connection, therefore, gives us not only a winding of a very simple character with a moderate number of terminals (18) capable of reconnection in a simple manner for a large number of different numbers of poles, but it also gives us the characteristic which was shown above to be desirable, viz. that of having an approximately constant flux on all numbers of poles. It is difficult to explain the cause of this in a simple manner, but one may say briefly that it is due to the fact that the number of sections in series between terminals having a given phase difference of, say, 120°, becomes gradually greater and greater as we increase the number of poles, or decrease the speed, so that as the rate of rotation of the flux wave gets less and less, due to the decreasing speed of the motor, the voltage across any section having a given number of turns also becomes less and less approximately in the same proportion, and thus about the same flux is needed to balance this voltage at all speeds.

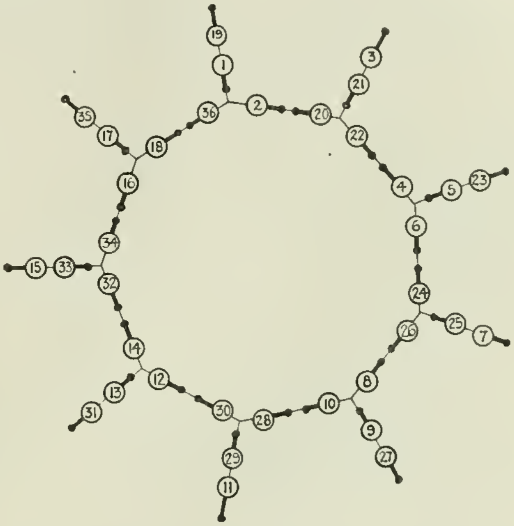


Fig. 7.

A further simplification is possible where, for instance, only odd numbers of pairs of poles are required and, consequently, diametrically opposite sections are always opposite in phase on every number of poles which a machine is required to give, and, therefore, may be permanently connected in series, mutually reversed.

The winding of such a machine is shown in Fig. 7 and, as will be seen, has only 9 terminals, capable of operating on 2, 6, 10 and 14 poles, and, with a slight further modification, on 22 and 26 poles. This winding is, I believe, the simplest known multi-speed winding. It requires no more than 9 phases, while the original winding may require 18 phases.

## The Phase Converter.

Having described how the difficulties connected with designing a multi-speed winding have been overcome by means involving the use of a phase transformer or converter, it will next be desirable to describe how this apparatus is constructed in practice. In certain cases, e.g. where a single motor is operated from a generator which serves no other purpose, as in ship propulsion, no such transformer is needed, as there is no difficulty in winding the generator for the number of phases required, but in the majority of cases the machine, if it is to be of any practical use whatever, must operate from a power supply having, say, not more than three phases, and hence it is of vital importance to the practical success of the apparatus that this phase transformer should be not merely technically satisfactory, but should also be capable of being built at a very moderate price.

By restricting the number of phases to multiples of three, the transformers to be excited from a three-phase circuit may be simplified very materially, and it will be convenient to describe the transformer as used in connection with the winding previously referred to. This transformer does not differ externally in any way from the standard three-phase core-type transformer, built in the usual way with three exactly similar limbs. The connections, however, are as shown in Fig. 8, in which all the windings shown by lines parallel to one another are considered to be wound on the same limb of the transformer. Since the windings shown in this figure are drawn parallel to three straight lines at 120°, it follows that only three such limbs are needed.

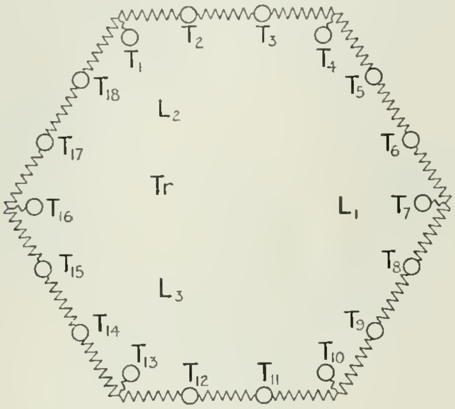


FIG. 8.

If we take a three-phase transformer having two secondary sections on each limb, and connect these sections in the manner shown, which may be called a hexagon connection, we obtain an apparatus from which six-phase currents may be derived by bringing out terminals from the corners of the hexagon. If, however, we tap the sides of the hexagon in the manner shown, winding on the three limbs, in addition, six small, auxiliary sections to be connected to the corners of the hexagon, it is possible without further elaboration to obtain no less than 18 phases, as has been amply proved in practice, the tappings shown in the diagram lying in a circle.

So far, we have regarded the hexagon winding with tappings as being the secondary, and have assumed that there is a primary winding which carries the three-phase currents. But if no voltage transformation is needed, as in this case, a separate primary is not needed, for the primary terminals may be connected direct to alternate corners of the hexagon, or even, in order to save extra terminals, to the extremities $L_1$, $L_2$, $L_3$ of three of the small, auxiliary sections wound on the transformer and corresponding to the secondary terminals $T_1$, $T_7$, $T_{13}$. This latter plan is adopted to avoid the necessity of bringing out three extra primary terminals.

By using the apparatus as an auto-transformer in this way we at once abolish the whole of the primary windings and, therefore, reduce the amount of copper on the transformer to half, or, in other words, double the rating of a transformer of a given size.

We do more than this, in fact, because the primary and secondary currents flowing in opposite directions in the same windings give a resultant which is very materially less than the secondary current alone. This is exemplified in Fig. 9, which shows the currents in the sections of the 30-phase transformer, which formed part of the original experimental machine which was constructed to test the present method of speed-variation in its earliest form, $L_1$, $L_2$ being the three-phase terminals.

It will be seen that the current in the neighbourhood of the three-phase terminals is much greater than at points intermediate between them, and, in fact, falls off to less than one-half at a point midway between the terminals.

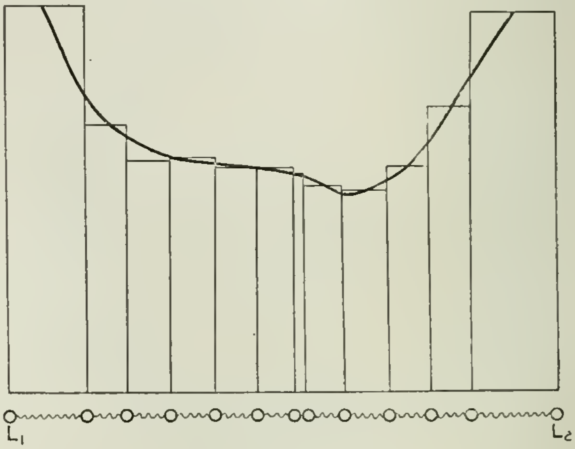


FIG. 9.

Fig. 10 shows a similar curve for up-to-date 9-phase and 18-phase transformers as now being constructed commercially by the Metropolitan-Vickers Electric Company for use with these machines. The same reduction in current per section at a point intermediate between the three-phase terminals $T_1$, $T_7$ is noticed here, and the analogy between the reduction of current in these transformers and the similar reduction which takes place in the armature of a rotary converter in sections intermediate between the tapping points may be referred to.*

As a result of this further reduction a phase transformer to transform a given amount of power, say from 3 to 9 or 18 phases, will require a size of transformer of only between 30 to 40 per cent of the rating of the transformer which will be required to convert the same amount of power, say from one voltage to another.

---

* I hope to publish the full theory of these phase converters on another occasion.

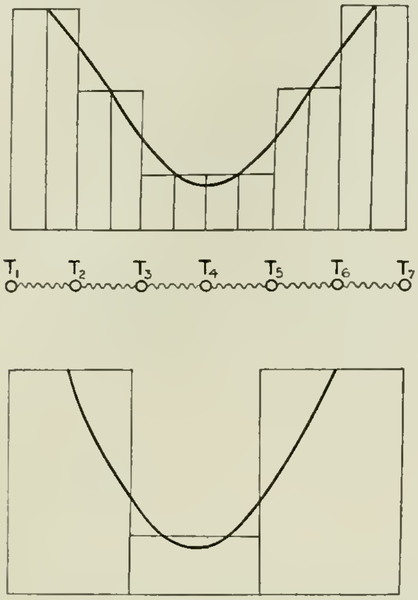


FIG. 10.

Still another economy which has the effect of still further reducing their capacity can be effected in the use of these phase converters. In a constant-torque motor giving a horse-power proportional to the speed, the amount of power taken will also be approximately proportional to the speed. For instance, the power taken at 750 r.p.m. will be only 0·75 times the power taken at 1 000 r.p.m., and if we can arrange the winding of our motor so that it is directly connected to the line when operating at 1 000 r.p.m., the phase converter not being used on that speed but coming into operation for the first time only at 750 r.p.m., we shall be able to reduce its capacity to 0·75 times the value which would be needed to supply the power required at 1 000 r.p.m., making it only 22 to 30 per cent of the capacity required to transform the whole power. By way of analogy to this plan, we may refer to an automobile gear box in which it is usual to give direct drive on the top speed, thereby reducing the amount of power to be transmitted by the gears. The above is the electrical form of the direct drive.

With speeds of 1 000 and 600 r.p.m. the rating of such a transformer may be only from 18 to 22 per cent of the transformer rating needed to handle the maximum power taken by the motor at top speed. It forms, therefore, by no means an expensive item in the equipment, much less so, in fact, than the transformer required with many types of variable-speed commutator motor, the capacity of which is proportional to the difference between the speed of the machines and synchronous speed.

*The controller.*—The only part of the equipment still to be described is the controller needed to effect the changes of connection between the phase transformer and the motor.

Different types of controller are, of course, required for different speed combinations. It is very easy to obtain combinations giving rise to very complicated circuits, but if care is taken to use the speed combinations best adapted to known types of winding and to choose the types of winding best adapted for the speeds required, the following rule for three-phase circuits may be enunciated :—

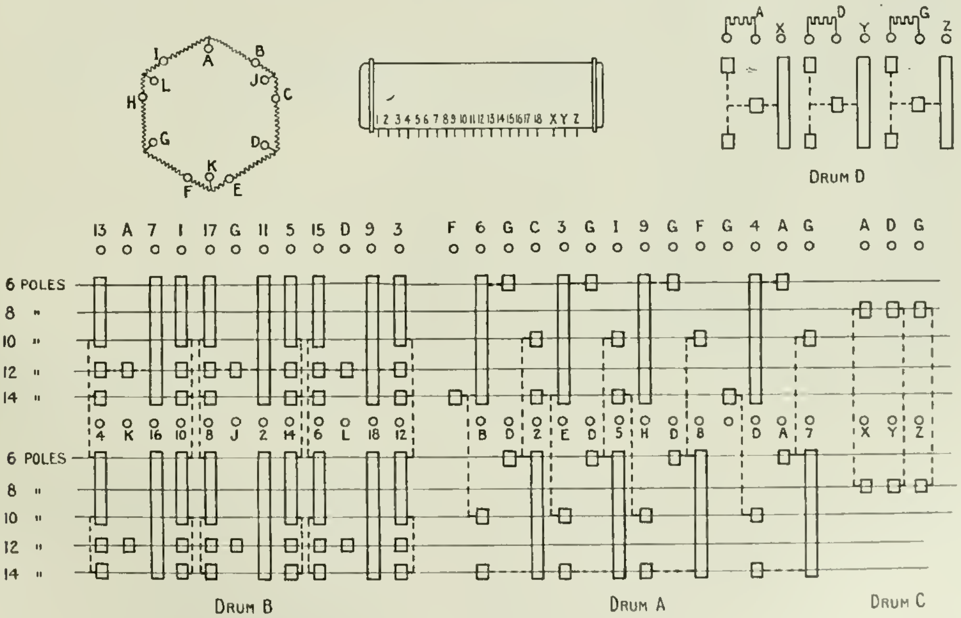

I
A
B
L
J
C
H
G
D
K
F
E
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 X Y Z
A
X
D
Y
G
Z
DRUM D
13 A 7 1 17 G 11 5 15 D 9 3
F 6 G C 3 G 1 9 G F G 4 A G
A D G
6 POLES
8 "
10 "
12 "
14 "
4 K 16 10 8 J 2 14 6 L 18 12
B D 2 E D 5 H D 8 D A 7
X Y Z
6 POLES
8 "
10 "
12 "
14 "
DRUM B
DRUM A
DRUM C

FIG. 11.

*A three-phase multi-speed motor for any number of speeds up to six, will require three times as many terminals as there are speeds.*

That is, a multi-speed motor with a single winding on each member may be built for any number of speeds up to six, requiring no more terminals than if each speed were produced by a different winding. This does not mean that any arbitrary selection of numbers of poles can be built with no more terminals than these, but that by suitably choosing the numbers of poles within the range of 3—1, these results may be obtained.

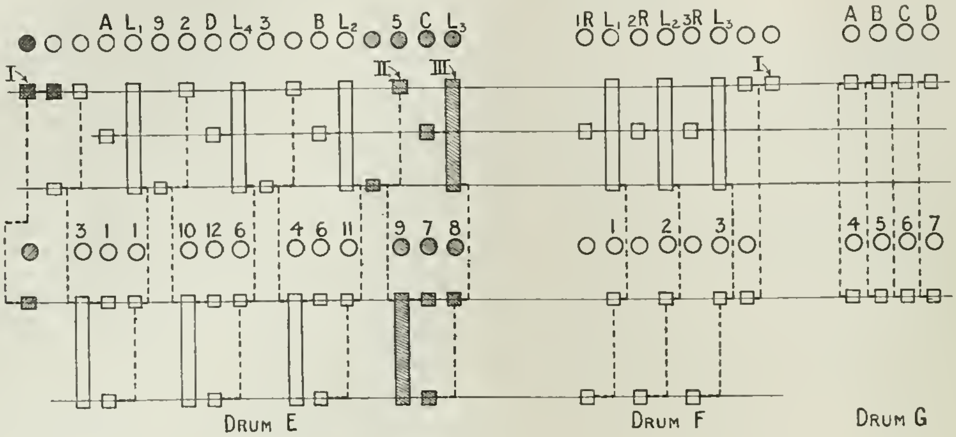


Fig. 12.

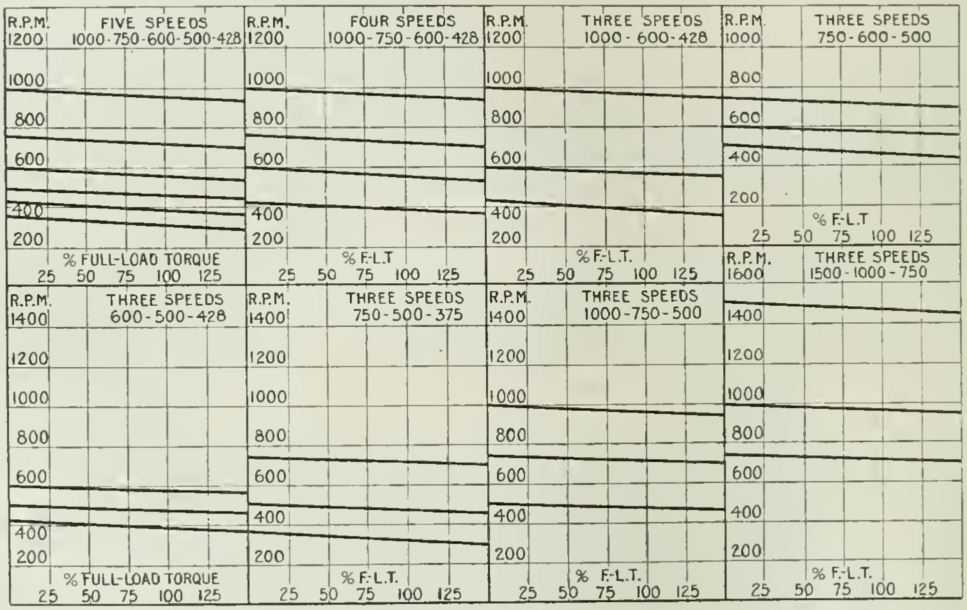


Fig. 13.

For instance, the winding described above (see Fig. 7) is usually arranged for 6, 10 and 14 poles, and requires 9 terminals, thereby obeying the rule, but a winding arranged for, say, 8, 10 and 14 poles, would not obey the rule, although windings for 6, 8 and 12, or 6, 10 and 12, could be designed to obey it.

Three is thus an amply sufficient selection of combinations for practical purposes, although there are a few abnormal combinations which fall outside the rule. Further research is rapidly lessening the number of these combinations.

A series of combinations adjusted with great care so as, on the one hand, to lend themselves to simple control, and on the other to cover most industrial requirements, is shown in Fig. 11, covering speed-ranges on 50 periods as follows :—

1 500/1 000/750 : Drum F
1 000/750/500 : Drum F
750/500/375 : Drum F
750/600/500 : Drums F + G
1 000/600/428 : Drum A
1 000/750/600/428 : Drums A + C
1 000/750/600/500/428 : Drums A + B + C

It will no doubt be agreed that these combinations cover practically everything that is needed for industrial purposes, and the control of all of them is sufficiently simple to be dealt with by a drum controller. Figs. 11 and 12, in fact, show diagrams of the drum controllers which are used to give these combinations and it will be seen that all, except that for the five-speed machine, are simple pieces of apparatus requiring only a single drum. The five-speed machine is usually built with two drums geared together, and forms the only case in which this is necessary, while in Fig. 13 has been assembled a series of speed/torque curves giving one example of each speed combination.

An important point in connection with these machines is, of course, the cost as compared with other means of producing the same results. In Fig. 14 is given a curve, for different horse-powers, for machines of this type as compared with a slip-ring induction motor with its control gear. This curve ignores entirely the enormous economy of current secured by an apparatus of approximately constant efficiency on all speeds.

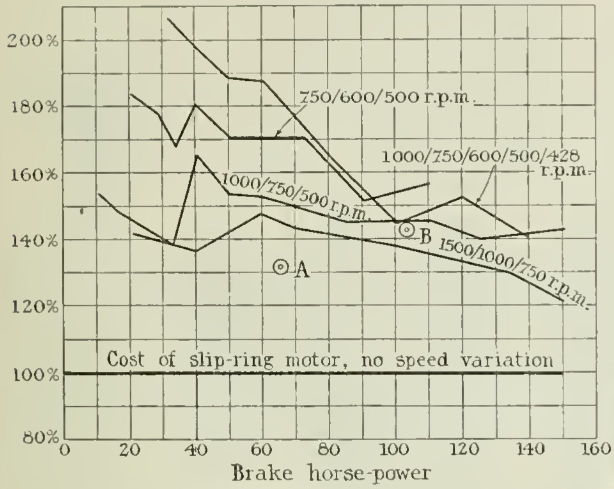


FIG. 14.—Percentage cost of multi-speed motors.

These controllers are suitable for small to medium sized motors, up to 200 h.p. The larger sizes, say from 200 h.p. to 800 h.p., are rather beyond the scope of a drum controller, and consequently an apparatus of a different type is employed. In Fig. 15 is shown such a large controller built by the Electric Construction Co., Ltd., the makers of these equipments, from which it will be seen that the controller consists of a slate panel bearing what are essentially four, nine-bladed two-way switches with vertical axes. The switches are of the finger type as in drum controllers and bear on studs mounted in the panel. They can be clearly seen in the lower half of the figure, while on the right and left of these switches are the terminals for the phase transformer and motor, respectively. The switches are opened and closed in the proper sequence by means of cams which appear immediately above the switches. For each speed, two of the switches make contact, thereby connecting the 18 terminals of the motor to the line or the phase transformer, in the different ways appropriate to different speeds.

It is found, by taking advantage of the following fact, that the switching may be simplified. One half of the connections for one number of poles, say 8, with the machine running clockwise, are identical with half the connections for another number of poles, say 10, with the motor running counter-clockwise. It conduces to simplicity of switching, therefore, if we make no change in these connections in changing from 8 poles to 10 poles, but merely interchange two of the three-phase lines, by means of the two contactors shown in the upper half of the panel which perform a quadruple function, as detailed below.

(1) They serve to reverse the three-phase connections when this is required, in order to economize switching.

(2) They are fitted with overload relays (shown immediately below them) so that they perform the function of a circuit breaker.

(3) In changing from one speed to the next in any multi-speed motor, it is necessary to open the circuit which in most forms of switchgear gives rise to a certain amount of arcing.

(I have for many years made it my practice in all such cases to open the circuit first, by a special switch designed with adequate blow-out apparatus, etc., to avoid arcing; then, while the motor circuits are completely dead, to change the connections, which may, of course, be done without any arcing, because they are not carrying any current; and, lastly, to close the main circuit again through the switch specially provided for that purpose. The contactors shown in the figure perform this function also.)

(4) The small switch on the right serves to open the contactor magnets, and causes them to act as a line switch, isolating the whole of the apparatus from the line as soon as it is opened.

The connections on the back of the board are not unduly complicated and are carried out by means of bare copper rods about $\frac{5}{16}$ in. diameter, in the standard manner. A mechanical interlock formed by the vertical rods below the contactors is fitted between the contactors and the cam shaft by means of an auxiliary shaft geared to the cam shaft, in the ratio of 1 to 4. The operation of this interlock is as follows:—On making a slight movement of the controller handle, the contactor magnets are opened. No further movement is possible until both the contactors are fully opened. When this has taken place the shaft is freed, and on moving it further the cams begin to move and alter the adjustment of the main switches. When the handle of the controller has moved, say, 180°, then the adjustment has been completed and the magnet circuit of the contactors is re-energized, closing them when the machine continues to operate on the new number of poles. Although these operations take rather a long time to describe, they do not, in practice, take more than two seconds.

### CHARACTERISTICS OF THE EQUIPMENT.

We now come to the description of the characteristics of machines of this type which are rendered available by the system of control just described. As has already been pointed out, squirrel-cage motors of the multi-speed type can find a very much greater field of utility than when used on a single speed only, since the chief drawback is almost completely overcome in the multi-speed form. This advantage, of course, relates to the starting.

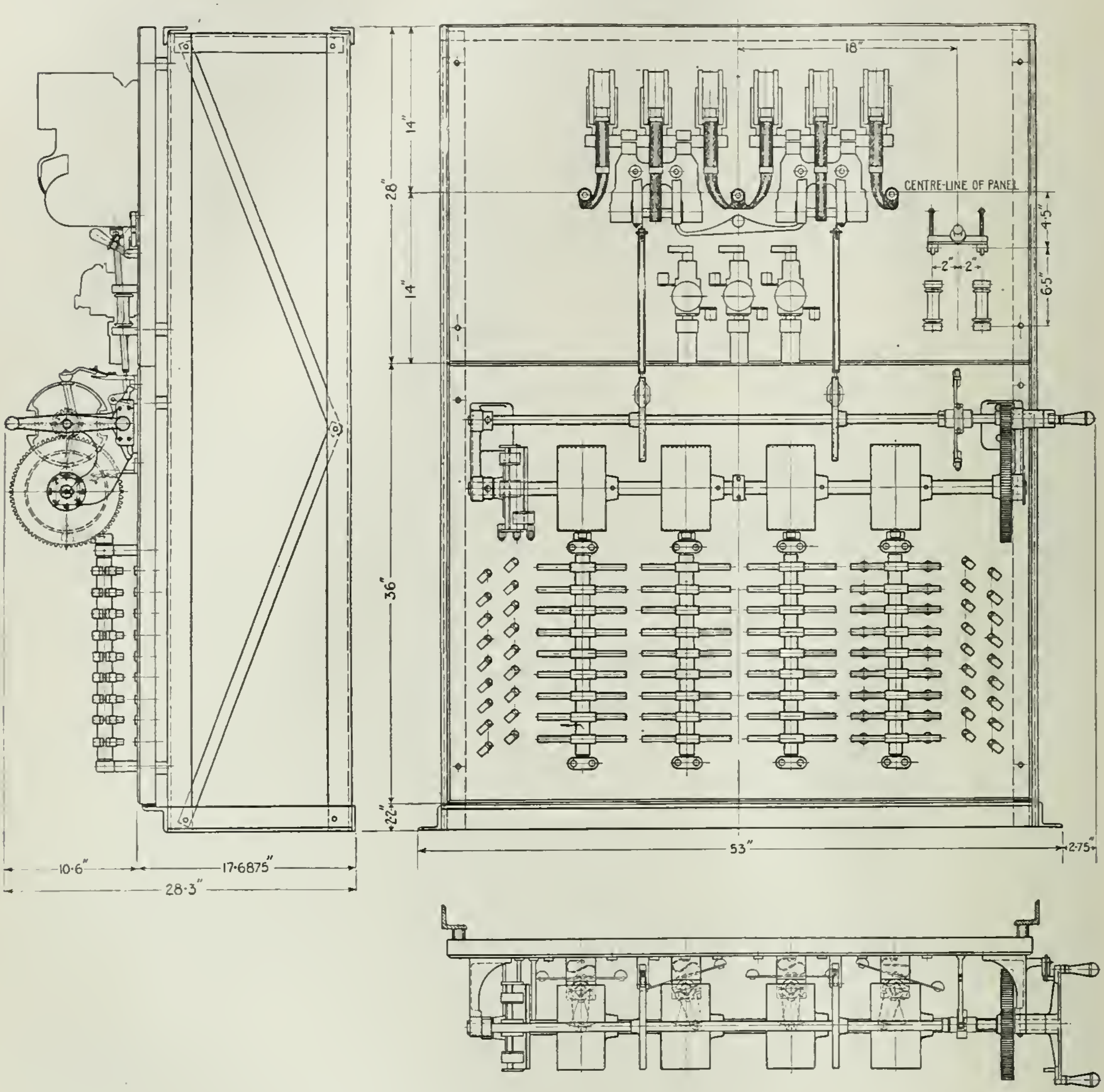


Fig. 15.—Arrangement of variable-speed motor control panel.

Consider, for instance, a 2-pole and a 4-pole motor, both having the same air-gap density. In the former there will be only two conductors in series, each lying in the middle of the pole-face, and the 4-pole motor will have four such conductors. If, therefore, we send the same current through the four conductors as through the two conductors, we shall obtain twice as much torque in the 4-pole machine as in the 2-pole machine, or, alternatively, for the same torque the 4-pole motor will require only half as much current; hence, if we can arrange a motor so that it starts on four poles and runs on two poles, to obtain a given starting torque it will take only half the starting current that it would require if it started on two poles. This is the origin of the very greatly improved performance of the squirrel-cage motor when used as a multi-speed machine. In squirrel-cage motors having a speed-range of two to one, or more, it is always possible to obtain full-load starting torque with not more than twice full-load current. All machines, of whatever size, having the same speed-range are capable of this ratio of starting torque to starting current, but if switched straight on to the line larger machines frequently take much greater current and give correspondingly greater torques. In most cases, therefore, the use of an auto-transformer is necessary with large machines. This may be seen from Fig. 16, in which is shown starting torque plotted against starting current for a 4-, 6- and 8-pole motor built by Messrs. F. & A. Parkinson, Ltd. It will be seen that with the 8-pole connection the machine gives 1·7 times full-load torque with twice full-load current. With a 6-pole connection it gives 2·4 times full-load torque with 3·6 times full-load current. With a 4-pole connection it gives 3 times full-load torque with 8·6 times full-load current.

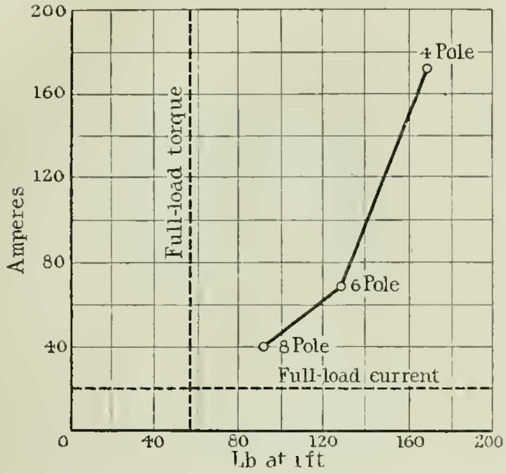


Fig. 16.

Another point frequently arising with multi-speed squirrel-cage motors relates to the current-rush on changing speed and the rate of acceleration from one speed to the next. Both these factors are under exact control by the use, in series with the motor, of primary resistance, which, of course, has the effect of reducing the voltage during the change of speed.

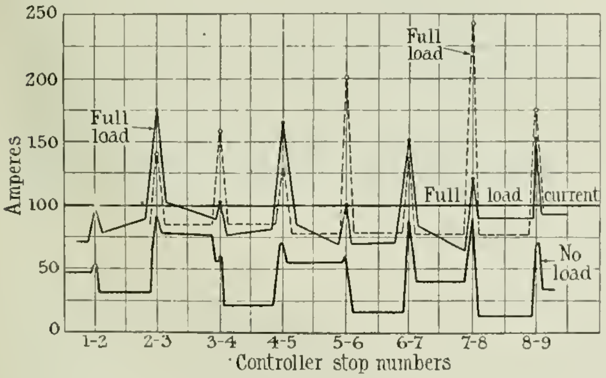


Fig. 17.

Returning to Fig. 15, in order to make use of this method of regulating the rate of acceleration between speeds, there is fitted on the panel by the side of those shown a third contactor which opens when they open, and which closes, due to the action of a dashpot, a few seconds after they close. This third contactor, when closed, bridges three resistances each placed in series with one of the lines; hence, directly the contactor opens, these resistances are placed in circuit, being adjusted to produce any desired rate of acceleration. They remain in series with the line during the operation of changing speeds, and are cut out when this operation has been completed.

In Fig. 17 are shown the current-surges produced in changing speed in a squirrel-cage motor arranged for all numbers of poles between 8 and 16, both with and without (dotted curves) a similar device, substituting an auto-transformer for the resistance. It will be seen that by its use the maximum current-surge is reduced to about one-half.

In a motor having a wide speed-range, the lowest speed-steps are very small and there is seldom any need for such a device. It is on high speeds, however, that it is needed. The figure illustrates the marked reduction in the current-surge on these higher speeds (shown towards the right of the figure), the device of course being adjusted to suit this case.

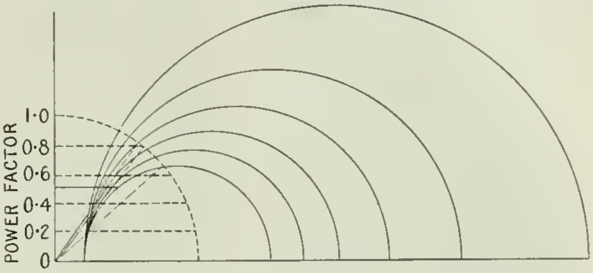


Fig. 18.

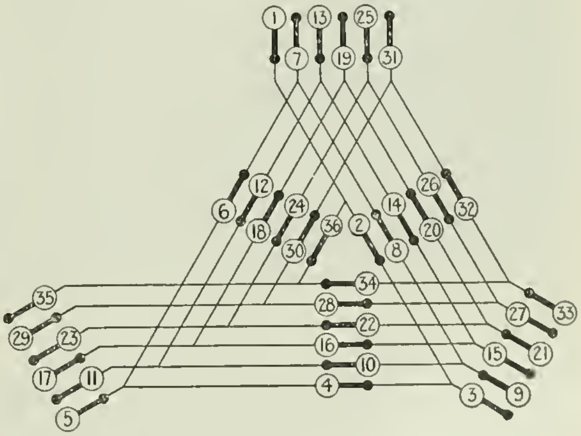


Fig. 19.

This method of starting and changing speed can be employed in motors up to several hundred horse-power, and renders the squirrel-cage motor adaptable to a vast variety of purposes for which it has never been found possible to use it before. A further extension of its field may be obtained by the use of centrifugal clutches, now coming into such general use, which may be arranged to operate at the lowest speed of the motor, the speed-change from this point being arranged in the manner just described.

To sum up, the sequence of operations to change speed in the case of a squirrel-cage motor, for instance, would be as follows :—

(1) The first movement of the controller handle causes the contactor to open, thereby cutting off the supply from the installation and rendering it " dead."

(2) A further movement of the controller handle opens the " switch-units " and recloses them in the correct combination to suit the next speed and, as the supply is cut off meanwhile, the change takes place without any sparking.

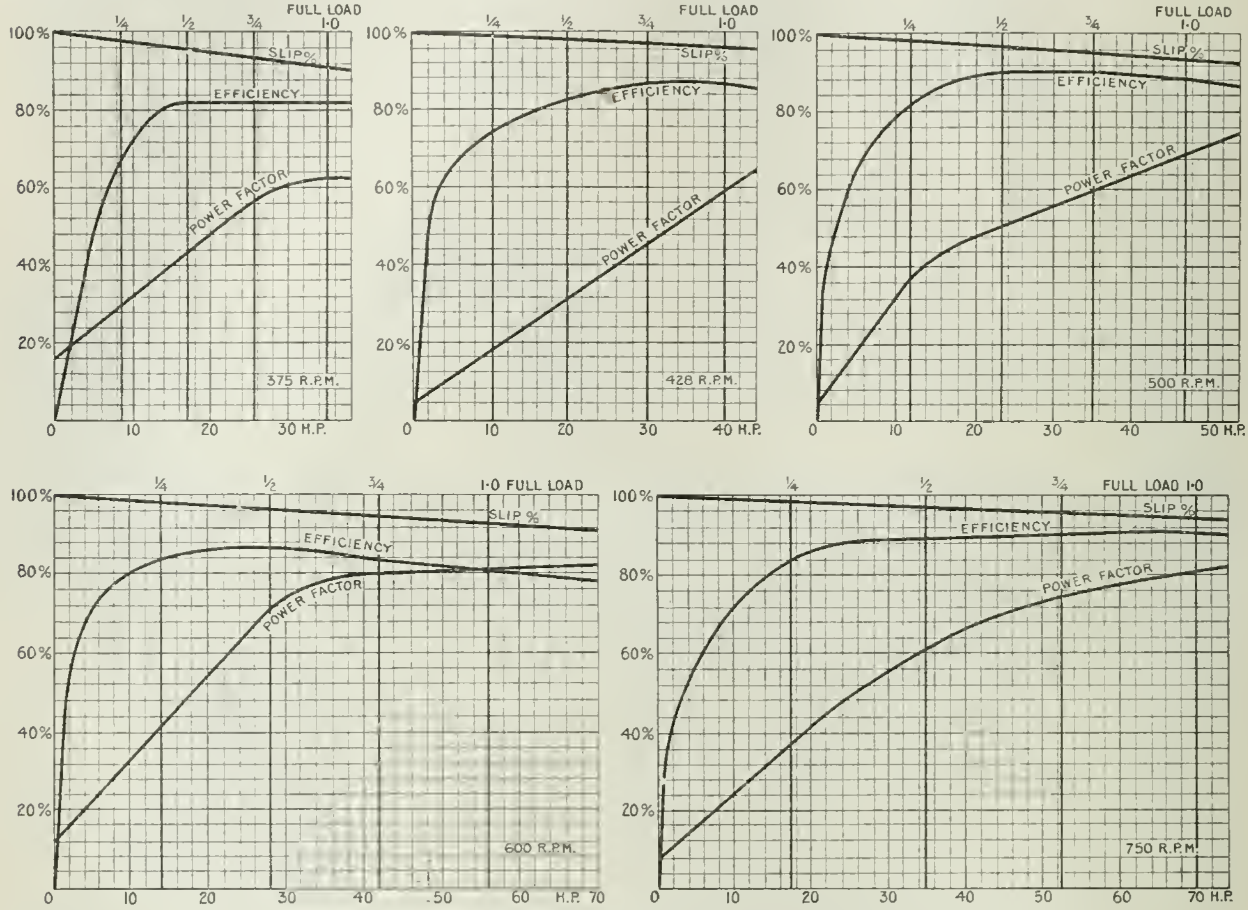


FIG. 20.—Performance curves with high-resistance rotor.

(3) When the controller handle has been moved to the notch corresponding to the speed desired, the contactor closes again and the circuit is re-established, the whole operation of changing speed taking approximately two or three seconds and being accomplished by one movement of the controller handle. In Fig. 18 is shown a series of circle diagrams for such a multi-speed motor operating on all numbers of poles from 6 to 16 and absorbing the same magnetizing current in all cases. These diagrams assume that the leakage coefficient is proportional to the number of poles, thus being twice as great in a 12-pole machine as in a 6-pole one. It will be shown below that this assumption is very nearly fulfilled in this type of machine.

This figure shows clearly the cause of the very great economy in starting current which is found in practice and was illustrated in Fig. 16. It will be seen that with 16 poles the motor takes about one-third of the starting current required with a 6-pole connection. Since the motor gives the same torque at all speeds, the ordinates to each circle represent the torque to a scale such that the torque represented by 1 mm on the diagram is proportional to the number of poles. Hence, in spite of the small current consumption, the motor can yield a powerful starting torque at the lowest speed.

*Slip-ring motors.*—It is possible to design a rotor winding for a machine having any number of speeds which shall give genuine slip-ring control up to one of these speeds, for instance, the top speed, and operate as a short-circuited secondary winding on all other speeds. One convenient way of effecting this result is by using such a winding as is shown in Fig. 6 but permanently connected so as to be capable of direct connection to the line. This connection is shown in

Fig. 19 and it will be seen that, as so connected, the winding requires no more than three terminals and can therefore be connected to the usual number of slip-rings.

On all other numbers of poles than six, however, the winding would require more than three terminals to enable it to be connected to any outside circuit, and if these terminals are short-circuited the winding is also internally short-circuited. Hence, the secondary currents which on 6-pole operation flow through the slip-rings, on any other number of poles flow through the internal circuits of the winding and do not pass through the slip-rings at all.

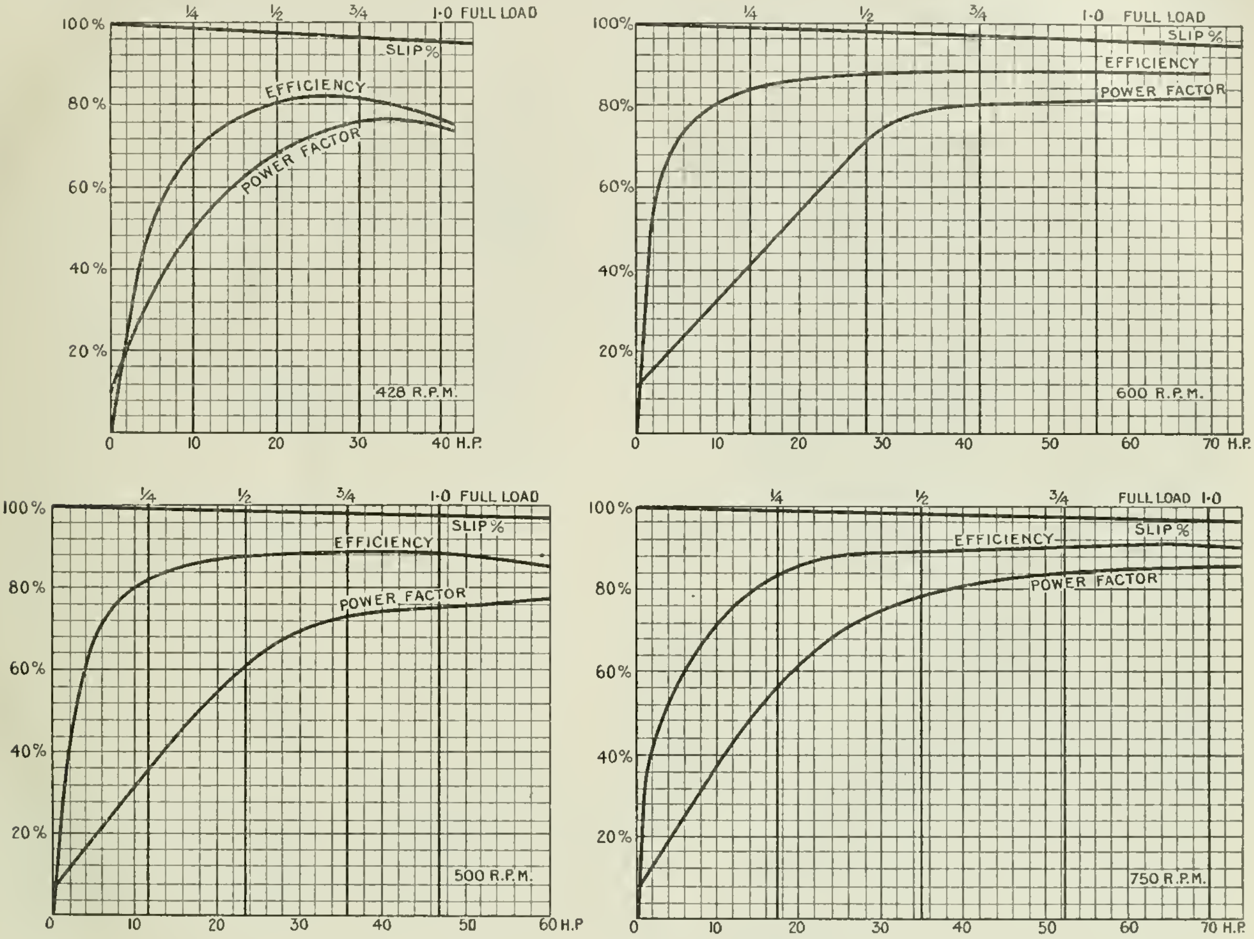


FIG. 21.—Performance curves with normal low-resistance rotor.

By means of this construction a motor is produced which can be arranged to be accelerated, by means of an ordinary resistance connected across its three slip-rings, from standstill to any one of its six speeds, starting, if desired, with from 2 to 2½ times full-load torque. On reaching the speed at which it is desired to run, a movement of the controller handle changes the number of poles of the motor to the desired value, when the currents in the rotor winding are automatically diverted from the slip-rings and continue to flow in closed circuits in the winding.

The operation of starting the slip-ring motor on any other than the top speed is therefore as follows :—

(1) Set the controller to the starting position which will produce in the motor a number of poles corresponding to the top speed.

(2) Gradually close the starting rheostat, when the motor will speed up.

(3) When the motor has reached the speed desired, which will of course be less than top speed, move the controller from the starting position to the running position corresponding to the speed at which it is running. This will have the effect of changing the number of poles to that corresponding to the controller notch employed, when the starter is automatically cut out as already described and the motor continues to run with its rotor short-circuited.

(4) The starter may now be open-circuited at leisure.

A tachometer may be provided in order to enable the operator to know the proper moment to change from starting to running position.

In Figs. 20 and 21 are shown some curves of efficiency and power factor of a 70 h.p. motor arranged to give all numbers of poles from 8 to 16.

Fig. 20 shows efficiency, power factor and slip curves for the 70 h.p. motor referred to above, arranged to give all numbers of poles from 8 to 16. These curves correspond to the results obtained when fitted with a high-resistance rotor adapted to give the powerful torque required in connection with this motor.

Fig. 21 shows corresponding curves for the same machine when fitted with a normal low-resistance rotor commonly used with squirrel-cage machines. Comparing these two sets of curves, a result will be noticed which at first appears rather strange, namely, that the efficiencies of the machine with a high-resistance rotor and with a low-resistance rotor are not very different for the same speed, while the power factor of the machine with high-resistance rotor is a good deal less than that of the machine when fitted with low-resistance rotor.

This is due to a method which can be employed in the induction motor to enable a high-resistance rotor to be employed without loss of overall efficiency. The torque of the motor is, of course, proportional to the product of ampere-conductors by flux density. If, therefore, we compare two motors having, say, flux densities in the ratio of $1\cdot5$ to 1, then in order to give the same torque they will require a number of rotor ampere-conductors in the ratio of 1 to $1\cdot5$, the machine having the stronger flux density requiring only two-thirds of the current in the rotor bars required by that having the smaller flux density. Two-thirds of the rotor current means of course four-ninths, or less than half, of the rotor $I^2R$ loss and, consequently, if we desire the resistance loss to be the same in both cases, the machine with the stronger flux density may have $2\frac{1}{4}$ times the rotor resistance of that with the weaker flux density.

This method was adopted in the motor illustrated in the above figures, which by means of tappings on the transformer was adapted to operate with either a strong or a weak flux. The strong flux used with the high-resistance rotor involves, of course, low power factor, and this is the explanation of the nature of the curves shown. By using stalloy steel punchings the iron loss was reduced to such a small proportion of the whole that the increased iron loss due to the stronger flux produced only a negligible effect on the efficiency.

Thus, by this process the squirrel-cage motor can be adapted to give any desired starting torque, without loss of efficiency, wherever we are prepared to sacrifice power factor to obtain this result, or to use additional power-factor-compensation devices such as condensers.

*Power factor and efficiency.*—Referring to the curves given above, it may be seen that the characteristics of the machine as regards power factor and efficiency are, broadly speaking, as follows :—

The efficiency remains very nearly the same at all speeds, though there is a slight reduction at reduced speeds, due, broadly, to the fact that the losses remain approximately constant at all speeds, while the output, of course, falls off in proportion to the speed. In the larger sizes, this reduction in efficiency will seldom exceed 5 per cent. The efficiency at top speed is, of course, practically the same as in a standard motor. The power factor also varies, as we change speed, to a somewhat greater degree than the efficiency, this variation being due, broadly speaking again, to the fact that the magnetizing current remains the same at all speeds, while the true power input falls off proportionately to the reduction of speed. Again, in the larger sizes this variation will seldom exceed 10 per cent.

The only thing which needs to be borne in mind from the power supply point of view is that these machines absorb a constant amount of wattless current at all speeds, and that this amount is not greater than that absorbed by a standard machine having the same rating. Perhaps it may serve to make the matter clearer if we compare the equipment with a standard motor driving through a gear box, a load which requires constant torque at all speeds. At top speed the motor is fully loaded and operates with its best power factor and efficiency. As the speed and the load are reduced by changing gear, the output of the motor falls off and with it the power factor and efficiency to some extent. To almost exactly the same extent do the power factor and efficiency of the equipment described fall off when the load is reduced ; in fact, the controller described above may be regarded as an electrical method of changing gear.

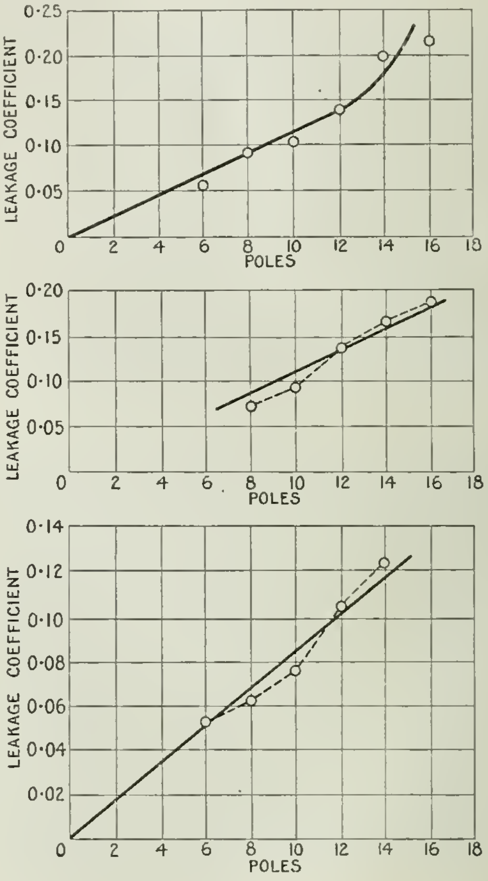


Fig. 22.

Reference has been made above to the fact that the leakage coefficient of these machines is practically proportional to the number of poles, and in Fig. 22 are shown some curves of leakage coefficients plotted against the number of poles. These curves illustrate this feature. Such curves, it is believed, will be of considerable interest to designers, and clearly could not be obtained from any other type of motor except one retaining an absolutely identical winding on all numbers of poles. Comparisons have frequently been made between motors having different numbers of poles, but this, of course, is not at all the same thing as in the case of a single multi-speed motor.

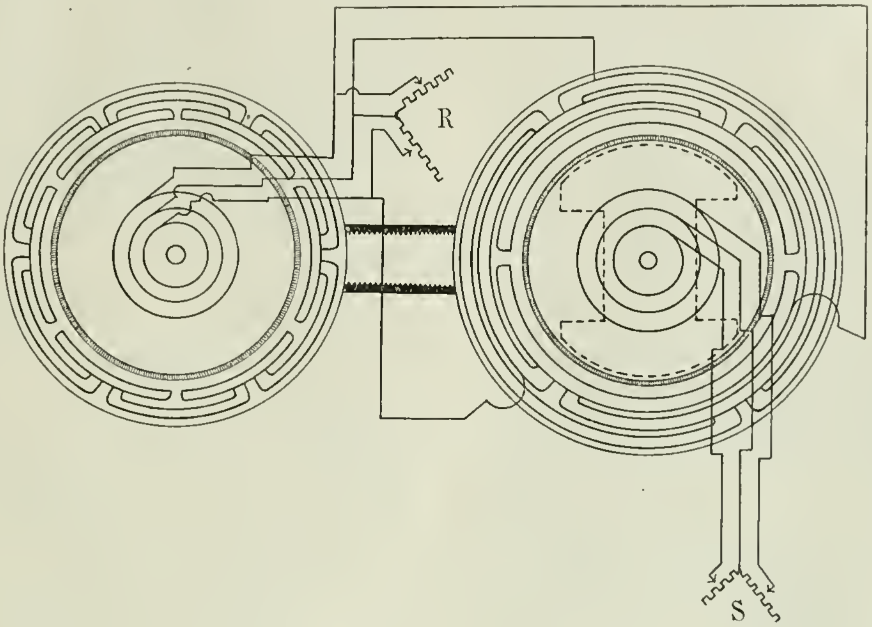


Fig. 23.

## Part 2.

### The Cascade Motor.

As previously pointed out, a second line of progress in the development of the induction motor leads in the direction of the internal cascade machine, as originally invented and developed by Mr. L. J. Hunt, but which has recently undergone very great further developments which have adapted it to a very much larger field.* The cascade machine has been described before the Institution several times in recent years and therefore I need only describe its principles very briefly, laying more stress on the different practical forms which it assumes and on the functions which it is capable of performing in the general system of electric power supply.

We may first of all briefly recall the general principles of a cascade operation. In Fig. 23 are shown two machines mechanically coupled together, in which the slip-rings of the first are connected to the stator winding of the second. The second machine is assumed to be wound for two poles and the first for six, and the combination will run at 750 r.p.m. on a 50-period circuit, viz. at a speed corresponding to $(6 + 2)$ poles.

One of the marked advantages of a cascade set is that it is possible to obtain not only two efficient speeds but also resistance control from standstill to the lower speed and, in addition, resistance control from the lower speed to the top speed. If the rotor of the second machine is fitted with slip-rings, then, if the first machine is connected to the line and the slip-rings of the second machine are gradually short-circuited through a resistance, the machine will start and rise gradually in speed, being under complete control by means of the rheostat, to the lower of its two efficient speeds, which it reaches when the slip-rings are completely short-circuited. If we now connect a similar resistance across the slip-rings of the first machine, then, on gradually short-circuiting them, the machine will rise from its lower efficient speed, say 750 r.p.m., to the higher, 1 000 r.p.m., which it reaches when the slip-rings of the first machine are short-circuited, and the second machine is thereby entirely cut out of action.

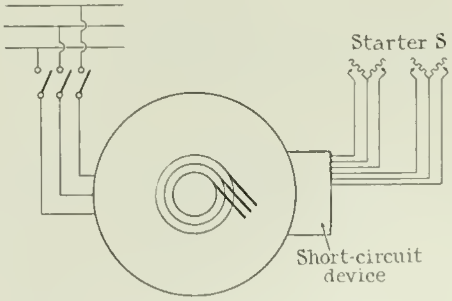


Fig. 24.

The advantages of these characteristics are, of course, very great, and the peculiar merit of Mr. Hunt's invention consists in having enabled us to realize them practically in one machine instead of two, whereby all the disadvantages of poor power factor and efficiency and higher first cost, which are inherent in the use of two distinct machines, are avoided.

---

* F. Creedy: "Some Developments in Multi-speed Cascade Induction Motors," *Journal I.E.E.*, 1921, vol. 59, p. 511.

How this has been accomplished has very recently been described before the Institution,[*] so I will not discuss it again. It will be sufficient to say that the final result is a motor as shown in Fig. 24 having only a single winding on each member, the stator being connected, on the one hand, to the line as a primary winding, and on the other to a starter as shown, the resistance of which is gradually cut out in order to bring the machine from standstill up to its cascade speed. This having been done, on further short-circuiting the resistances R placed across the slip-rings the motor will rise from its cascade speed to its maximum speed.

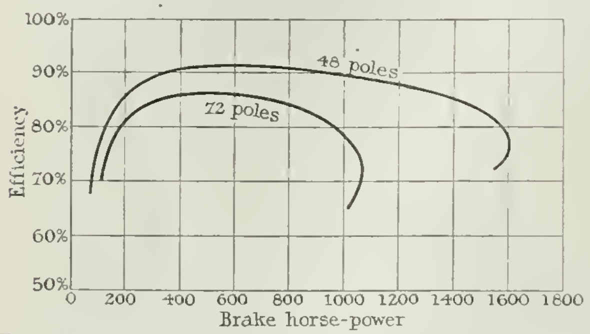


FIG. 25.—Efficiency curves of a Sandycroft two-speed cascade 3 000 volt, 50 period rolling-mill motor; 860 b.h.p. at 120·5 r.p.m., and 576 b.h.p. at 81·6 r.p.m.

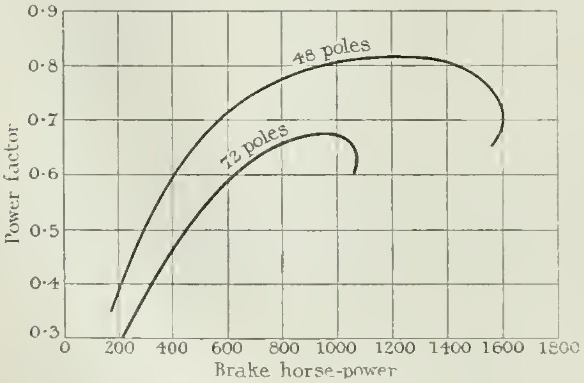


FIG. 26.—Power factor curves for the motor referred to in Fig. 25.

An alternative method of operation consists in having both sets of slip-rings on the one rotor and thus obtaining for a particular combination of numbers of poles a machine with six slip-rings, the same number as are required in the cascade set. By short-circuiting three of these through a resistance, the machine is brought up to its lower speed, while by short-circuiting the remaining three it is brought up to its top speed. This method of starting is particularly advantageous for high-tension machines, since it avoids all high-tension switchgear and forms the only multi-speed induction motor in which it is possible to change speed without opening the circuit.

Internal cascade machines of this type, however, as built up to recent years were restricted to machines having their lowest efficient speeds corresponding to numbers of poles of 12, 18 and 24, etc., and to two definite ratios of speeds, namely, 3—2 and 3—1. While much work has been accomplished by this means, and great credit is due to Messrs. Sandycroft for the results obtained, it is believed that now that these limitations have been removed they will be able to cover a much wider field. Machines can now be built the lowest speeds of which correspond to any number of poles exceeding six and having, in theory, any desired ratio of speeds. Certain practical limitations to the speed ratios of two-speed motors are introduced by the rule as regards the number of slip-rings required by such a machine. This rule is as follows :—

*A motor to give a top speed corresponding to* M *poles and a bottom speed corresponding to* (M + N) *poles, will have a number of slip-rings equal to* (M + N)/(G.C.M. of M and N).

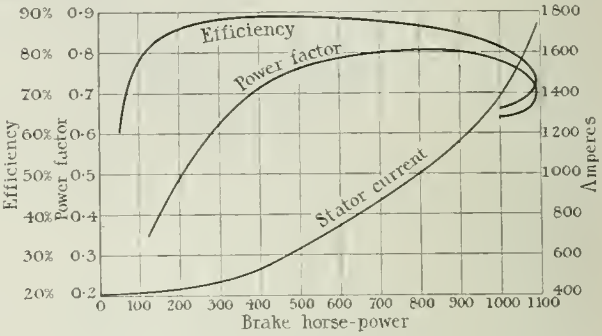


FIG. 27.—Performance curves of a single-speed, 450 b.h p., 122 r.p.m., 500 volt, 50 period rolling-mill motor.

For cases where either $M$ or $N$ is large and where there is no common factor between them, clearly the number of slip-rings may be higher than is desirable, but setting aside these cases a very large number of new ratios become available. For instance, confining ourselves to apparatus requiring less than six slip-rings the following combinations, among others, can be built:

| Ratio | Speeds offered on 50 periods |
|---|---|
| 4—3 | 1 000/750 or 500/375, etc. |
| 5—4 | 750/600 or 375/300, etc. |
| 5—3 | 500/300 or 250/150, etc. |
| 5—6 | 600/500 or 300/250, etc. |

Some of these ratios are particularly important in certain classes of application, e.g. in mine fan motors where the power developed decreases as the cube of the speed. In these cases the reduction from full speed to two-thirds is sometimes found to be too great and a smaller reduction, say from full speed to 5/6 or 4/5 full speed, may meet the conditions more fully.

Besides this, only a very small reduction is necessary for flywheel sets and in this case the new ratios prove also of very great advantage.

---

[*] F. CREEDY: "Some Developments in Multi-speed Cascade Induction Motors," *Journal I.E.E.*, 1921, vol. 59, p. 511.

The slip-regulator operating the rotor circuit of a two-speed cascade motor wastes very much less power, and consequently may be of very much smaller and lighter construction than when used with an ordinary single-speed induction motor.

Curves relating to a two-speed rolling-mill motor of considerable size in which these properties of the cascade motor are made advantageous use of are shown in Figs. 25 and 26, which, I think, will be found to be self-explanatory. In Fig. 27 are shown performance curves of a single-speed cascade rolling-mill motor which was adopted on account of the absence of slip-rings, and the singularly substantial construction of the rotor winding, both of which are of great importance in steel-mill work.

So far we have dealt with the cascade set pure and simple, in which the speed-change can be effected without opening the stator circuit. By combining the cascade method with the pole-changing method previously described, machines may be built for three or more speeds. To do this the primary winding is adapted for several numbers of poles, which may be done in a variety of ways, although, due to its double function as primary of the first machine and secondary of the second machine, this is more difficult than where the winding only has to serve a single function as described in Part 1. The same cascade speed may be obtained by means of several different combinations of numbers of poles; for instance, a cascade speed of (8 + 4) = 12 poles, may also be obtained from (10 + 2) = 12 poles, and it has been proved that a secondary winding which is adapted to work with (8 + 4) poles will work equally well with (10 + 2). Hence, if we have the primary winding of the machine arranged for 8 poles, and the secondary winding adapted to (8 + 4), the machine, if running on its cascade speed, will go at the speed corresponding to 12 poles and, if we short-circuit the slip-rings, will rise from the 12-pole speed (500 r.p.m.) to the 8-pole speed (750 r.p.m.).

If, while the machine is running at its cascade speed (500 r.p.m.), we change the number of poles in the stator winding from 8 to 10 which, of course, involves a switching operation, there will be no change in the speed of the motor. If, however, we now short-circuit the slip-rings, the machine will gradually rise from the 12-pole speed (500 r.p.m.) to the 10-pole speed (600 r.p.m.). Thus we have an apparatus preserving the unique characteristic of the cascade machine, viz. that of permitting a gradual regulation between speeds and yet having more than two speeds.

Large, low-speed motors having speeds in the ratios just mentioned, e.g. motors running at 187/150/125 r.p.m., prove very advantageous in certain cases, for instance in rolling mills. The principle just described may be extended to machines having four or more speeds, in all of which cases the cascade machine will rise from its cascade speed to any of the speeds for which the stator winding is adapted.

For instance, a four-speed machine adapted to speeds of 750/500/375/300 r.p.m. may be built. The limitations to the number of speeds which can be obtained by this process are due to the difficulty of designing the stator winding for a large number of different numbers of poles, and at the same time adapting it to act as a secondary.

*Other applications of the cascade machine.*—In addition to its usefulness as a multi-speed machine, the cascade induction motor has a wide field of utility in other directions to which we may briefly refer. It has been pointed out that it may be started with a powerful torque and brought up to its cascade speed by merely cutting out a resistance connected across the tappings on the stator winding. Such a machine will have a completely short-circuited rotor without external connections, and it realizes the old desideratum of a squirrel-cage motor with slip-ring characteristics.

I need not do more than very briefly point out the great advantages of such a construction in dusty or inflammable atmospheres, and its much greater reliability.

It has often been pointed out that the power factor of the cascade motor is materially higher than that of the standard type of slip-ring induction motor running at the same speed. This is due to the following two causes :—

(1) A cascade motor running at 500 r.p.m. is wound for 8 poles, and therefore the pole-pitch is 50 per cent greater than in a standard 12-pole motor. The difference in leakage between an 8-pole and a 12-pole motor is very considerable, as may be seen in Fig. 22.

(2) The simple cascade rotor winding, approximating as it does more nearly to a squirrel-cage winding than to an ordinary slip-ring winding, gives rise to a much lower leakage, and these two causes, acting in conjunction, account for the higher power factor of the cascade machine.

Another application, which may possibly prove to be the most important of all, is as a synchronous machine for the purpose of improving the power factor. Such a machine has marked advantages over any other form of synchronous apparatus.

The chief drawback to synchronous sets for improved power factor has up to now been their high cost, which is largely due to the amount of auxiliary apparatus they require, in addition to the large number of exciting ampere-turns necessary to give an adequate overload capacity. Both these features are very much reduced in the synchronous cascade set.

In order to understand this, consider a cascade set, consisting of two machines, the stator of the second of which is electrically coupled to the slip-rings of the first, while they are mounted on a common shaft. Let the second machine be arranged for two poles and the first machine for six poles, then, as is well known, the combination will run at 750 r.p.m. on a 50-period circuit, viz. at a speed corresponding to (6 + 2) poles.

The second machine will receive from the slip-rings a frequency one-quarter the line frequency, viz. 12·5 periods per second. As is well known, the rotor of the second machine of the cascade set may be of any desired type, e.g. either of the squirrel-cage type, the slip-ring type, or even the revolving field of a synchronous motor.

On the rotor of such a secondary synchronous motor a number of ampere-turns must be provided, equal to that on the stator, plus the amount necessary to produce the magnetic flux in this secondary machine.

Now, in the internal cascade motor, the ratio of the total flux (flux per pole × number of poles) in the parts corresponding to the primary and secondary motors in the cascade set which we are now discussing, is fixed by the construction of the rotor winding and is nearly equal in both cases. Consequently, a cascade set corresponding to the internal cascade machine would have the same total flux in both its constituent machines. If the magnetic densities are the same, as they must be, since both fluxes are carried by the same iron, it follows from fundamental electromagnetic laws that the turns per pole necessary to produce these fluxes in the primary and secondary machines are also nearly equal, and, since there are only two poles in the secondary motor to be excited instead of eight poles in a synchronous motor of normal construction running at the same speed (750 r.p.m.), only one-quarter of the exciting watts are needed.

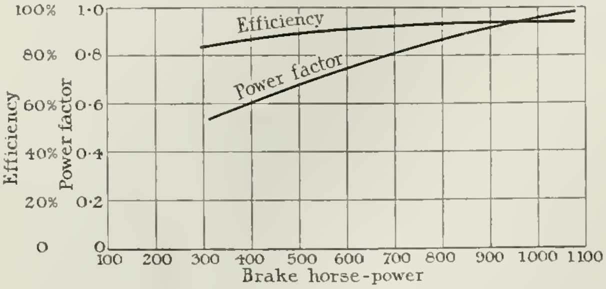


Fig. 28.—Efficiency and power-factor curves of a two-speed, 3 300 volt, 50 period, three-phase synchronous fan motor; 850 b.h.p. at 187·5 r.p.m., and 260 b.h.p. at 125 r.p.m Curves for 187·5 r.p.m.

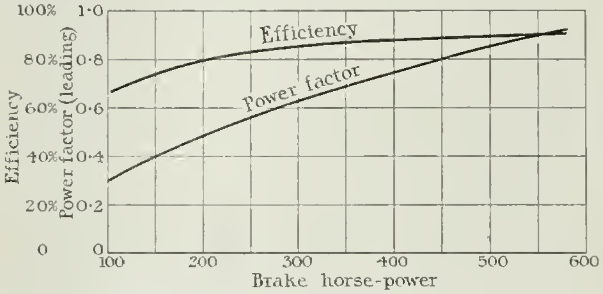


Fig. 29.—Efficiency and power factor curves of the motor referred to in Fig. 28, at 125 r.p.m.

This shows itself in practice in the very much reduced size of exciter required by a cascade synchronous motor as compared with the older type. This characteristic renders the synchronous cascade motor feasible from the point of view of cost in much smaller sizes than any other type of synchronous machine. Figs. 28 and 29 show characteristics of a two-speed cascade synchronous machine of this type.

## Summary of Characteristics of Variable-speed, Alternating-current Motors without Commutators.

(1) A large variety of speed combinations is available, giving any number of speeds up to five (or six with a panel-type controller), e.g. those shown in Fig. 13, all of which are capable of control by simple types of drum controller and some are capable of being built economically down to 2 or 3 h.p.

These have, for the most part, the characteristics of machines with short-circuited secondaries, but are capable of starting at full-load torque with not more than twice full-load current, and the rate of acceleration in changing speed under full load is under exact control by simple means.

(2) A slip-ring type of motor capable of any number of speeds up to six and capable of accelerating under, say, 2–2½ times full-load torque from standstill to any of such speeds.

(3) The two-speed cascade motor capable of accelerating from standstill to its lowest speed under 2–2½ times full-load torque by resistance control, and then rising from its lower to its higher speed by short-circuiting a resistance connected across the slip-rings. These two speeds may have practically any desired ratio. Speed-change is here effected without opening the stator circuit.

(4) A multi-speed cascade machine capable of starting and accelerating to its lowest speed in the manner just described and then of rising from that speed to any one of its other speeds on short-circuiting the slip-rings.

I believe it will be admitted, as a result of what has been said above, that it is possible to meet practically every condition of variable-speed working required in industrial practice by an appropriate method of control applied to the ordinary induction motor, this control involving no continuous waste of power or other undesirable features, and consisting merely of simple and well-known types of switchgear and, in some cases, small transformers.

For the few remaining cases in which an absolutely gradual speed-variation is required without loss of power, we have the polyphase commutator motor, with movable brushes as was described, for instance, in the paper by Mr. Teago.*

Hence I feel that I should have no difficulty whatever in recommending a suitable variable-speed alternating-current motor to meet the conditions of any industrial problem whatever, and that no cases remain in which it is either necessary or desirable to convert to direct current for the sake of obtaining variable-speed operation.

## Discussion before The Institution, 4 January, 1923.

**Mr. L. J. Hunt:** I propose to confine my remarks mainly to the windings. It is, I think, a remarkable fact, and one which will appeal to the manufacturer, that the winding which has made practicable the building of commercial cascade motors is apparently also the best winding for variable-pole motors. I refer to the old cascade rotor winding which, as the author has shown, gives quite remarkable results when used as a stator winding for change-pole motors. Before the author studied this winding it had been used only for three-phase and six-phase currents, and as a variable-pole winding produced either $x$ or $2x$ poles.

---

* *Journal I.E.E.*, 1922, vol. 60, p. 328.

The unit winding was a six-sided figure which served for a six-pole cascade motor. The other windings were built up as multiples of this unit and so we had a 12-sided figure for 12 poles, an 18-sided figure for 18 poles, and so on, the windings being parallel connected. The author's first discovery was that these windings would always give a cascade speed corresponding to a number of poles equal to the number of sides, irrespective of the number of poles for which the stator was wound; thus an 18-sided winding would give a cascade speed corresponding to 18 poles with a stator connected for either 16, 14, 12, 10, 8, 6, etc., poles, the number of auxiliary poles produced by the rotor being the difference between 18 poles and the number of poles for which the stator is connected. Further, he found that when the slip-rings were short-circuited the winding would serve as a satisfactory secondary winding for any of the basal numbers of poles; that is to say, if the stator were connected for six poles the winding would serve as a six-pole secondary winding or, equally well, as a secondary winding for the other numbers of poles. This discovery immediately pointed the way to the remarkable developments which the author has shown us. When used as a rotor winding the difference in phase between the several slip-rings varies with the number of poles provided by the stator. It follows therefore that if we use this winding as a primary and supply it with currents, the phase of which can be correspondingly changed, we shall produce the same variations in the number of poles, and this the author has done by means of the beautifully worked-out phase transformer which he has described. Fig. 6 is familiar as the 18-pole cascade rotor winding, which before the author's discovery had been used only for basal numbers of poles of 12 or 6, corresponding to three-phase or six-phase currents; that is to say, this winding prior to these new developments had been used for only 6 or 12 poles or, in cascade, for 18 poles. The author has shown how very efficient it is when used as a stator winding for producing a large number of speeds. He made a further discovery applicable to both change-pole and cascade motors. He found that in the past we had needlessly confined these windings to three-phase and six-phase types, and he showed that an 8-sided winding would operate as an 8-pole cascade rotor, a 20-sided winding as a 20-pole machine, and so on. In his recent paper * he defined these windings as suitable for use with two fields having numbers of pairs of poles prime to one another and both odd. These windings greatly increased the possible speeds for which cascade motors could be wound, as they gave us 8, 16, 20, etc., poles. This greatly increased the scope of the motor, but further discoveries were made. Dr. F. T. Chapman, in his recent paper on "The Production of Noise and Vibration in Certain Squirrel-cage Induction Motors," † has proved that no unbalanced magnetic pull exists when a motor is subjected to two magnetic fields if the difference between the numbers of poles is greater than two. This further increases the possible numbers of poles for which cascade machines can be wound, as it shows that all speeds can be obtained excepting those corresponding to 2, 4 or 6 poles, because a 10-pole motor can be obtained by taking basal numbers of poles of 8 and 2, thus giving a 10-sided winding, and with the stator wound for 8 poles the rotor would produce a second field corresponding to 2 poles. These discoveries enormously increase the field for these machines. The author has referred to the reduced excitation required by synchronous cascade machines, and I have some figures derived from tests which show that a machine of this type with sufficient ampere-turns to give a maximum torque equal to twice full-load torque requires a net number of field ampere-turns equal to only 61·4 per cent of the total stator ampere-turns. If allowance is made for the cancelled bars due to the shortened pole-pitch of the windings, the figure is 4 per cent greater than the alternating-current ampere-turns. The following figures relating to ship-propulsion motors may be of interest. They relate to a unit driving one propeller shaft. This is arranged for full speed, two-thirds and one-half speed, and develops 20 000 b.h.p., 5 000 b.h.p. and 2 600 b.h.p., respectively, at the three speeds. At full speed the set runs as an induction motor, and at the other speeds as a cascade synchronous combination. At full speed (24 poles) the power factor is 0·91 and the efficiency 96·5 per cent, while at second speed (36 poles) the efficiency is 94 per cent and the power factor unity. At half speed (48 poles) the efficiency is 93·2 per cent with unity power factor. There are many points to be considered in the design of multi-speed motors, and two slides which I propose to exhibit show the great improvement which can be effected in the performance of these machines by using three groups of coils per pole, instead of three groups per pole pair. These figures relate to a 400-b.h.p., three-speed motor which was built many years ago. In the first place the stator was wound with three groups of coils per pair of poles, and the efficiencies and power factors obtained can be seen on the slide. At a later date the motor was reconnected with the coils arranged in three groups per pole, and the vast improvement in both efficiency and power factor is shown. At 20-pole speed the efficiency improved from 87 to 90·5 per cent and the power factor from 0·795 to 0·9. At 30-pole speed (cascade) the efficiency was raised from 80 to 87 per cent and the power factor from 0·665 to 0·79. These figures are rather remarkable, as they indicate the harmful effects due to the presence of extraneous fields.

**Dr. S. P. Smith**: The author's achievement in the field of the variable-speed induction motor is no mean one, and he has given us what we very much needed. The fact that the induction motor could not be made to vary its speed economically by any simple means has been one of the greatest drawbacks in its development. We have long had various arrangements of two machines and also of two windings on a single machine, but the author now shows how to make the ordinary squirrel-cage induction motor run at 2, 3, 4, 5, or even 6 economical speeds. In that way he has rendered us a very great service and has made it possible to avoid, in many cases, converting alternating into direct current. The author's multi-speed motor has advantages in addition to its speed-changing properties. With an ordinary squirrel-cage single-speed motor, if full-load torque is required at starting, something like 4 to 5 times full-load current is needed. Except in the case of small motors the supply undertaking would not allow this, and therefore a slip-ring motor must be used. The multi-speed motor, however, can give full-load torque with twice full-load current, which should not be objected to on large systems. Another advantage which should be emphasized is that the multi-speed motor will give constant torque at all speeds. The shunt motor has not this advantage. Assuming constant armature current in a shunt motor, the torque falls off as the speed rises, so that the horse-power remains constant. What the user generally wants for many classes of drives, however, is constant torque, or output proportional to speed. This property can be obtained with the a.c. motor with or without a commutator. The reason is simple. In order to make the horse-power increase as the speed rises, the voltage must be increased. It is complicated to do this with direct current, but with alternating current it is usually a simple matter to utilize the motor fully under all conditions. Fig. A will enable the interior of the author's multi-speed motor to be seen from a different point of view. The arrangement is shown for a thirteen-phase transformer or phase converter. With 13 phases on the transformer the angle between the phases is $2\pi/13$ radians. The numbers in the figures refer to the numbers of the transformer phases. The top left-hand figure shows that the motor tappings 1, 2, 3, 4, etc., are connected to phases 1, 2, 3, 4, etc., of the transformer. Thus for one pole-pair, or $2\pi$ radians, we must go round the whole periphery. In the middle diagram on the top line the author would connect phase 1 of his transformer to tapping 1 of his motor, but phase 3 of his transformer goes to tapping 2 of his motor, and so on, so that the phase angle would now be $4\pi/13$. One pole-pair ($2\pi$ radians) is now accomplished with a half-tour of the stator winding, so that the motor has four poles ($p = 2$). Similarly the other possibilities give $p = 3$, 4, 5 and 6 pole-pairs. Thus the thirteen-phase transformer will give a six-speed motor. On the author's motor an 18-phase arrangement is used to simplify the connections, tappings, etc. By using the multi-speed or extended cascade motor, it may be possible to dispense with speed-regulating sets such as the Scherbius. It will be interesting to see whether these arrangements can be used for large, reversible sets such as rolling mills, winding engines, etc. There still remains, however, the need for power factor improvement and gradual speed-change, which may entail at times the use of a.c. commutator machines.

---

* *Journal I.E.E.*, 1921, vol. 59, p. 511.

† *Ibid.*, 1923, vol. 61, p. 39.

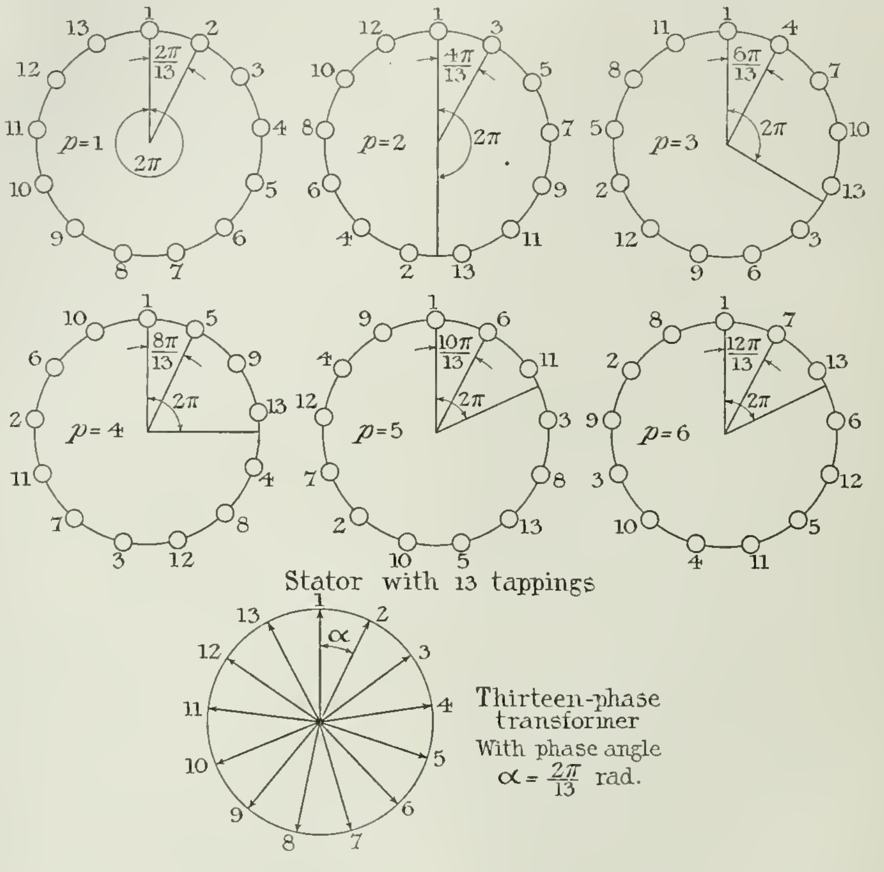


Fig. A.

**Mr. H. Jack**: In this country, due to the large number of relatively small power companies, the proportion of d.c. to a.c. motors has always been higher than in the majority of other countries. The tendency is, however, for the proportion of a.c. motors to increase considerably, and the need for a good variable-speed a.c. motor has become extremely important. It is generally admitted by designers that a motor with the simplicity and the possible speeds of the d.c. shunt motor would meet the market requirements. The fact that the d.c. motor has a commutator is not now considered a serious defect. In addition to comparing the motor described in the paper with the variable-speed d.c. motor, it is also possible to examine how far it meets the actual practical requirements of a variable-speed a.c. motor and to compare it with other multi-speed and variable-speed motors on the market, such as the ordinary change-pole motor and the a.c. commutator motor. For the past 15 or 20 years we have had 2-, 3- and 4-speed change-pole multi-speed a.c. motors. These motors have been robust and comparatively cheap, yet they have not met the requirements of a variable-speed motor. By adding a phase converter and an elaborate controller, the author has again given us a multi-speed rather than a variable-speed motor. The sum of the whole matter is, therefore, that in some cases two additional speeds can be obtained by the author's motor, as compared with the change-pole motors previously available. Considering that the 2-, 3- and 4-speed change-pole motors have failed to meet the requirements, I think that the number of cases in which the motor described in the lecture will come any nearer the requirements is extremely limited, as it still has practically all the defects of other multi-speed change-pole motors. The speeds available are too limited. For example, on 25 periods there is no speed between 1 500 r.p.m. and 750 r.p.m., and the next speed is 500 r.p.m. Hence, on a motor with a 2 : 1 speed-range there are only three available speeds. If the maximum speed is chosen as 750 r.p.m. there are still only three available speeds on a speed-range of 750 to 375 r.p.m. On 40 periods there is no speed between 1 200 r.p.m. and 800 r.p.m., and the next possible speed is 600 r.p.m., and similarly on 50 periods there are no possible speeds between 1 500, 1 000 and 750 r.p.m. Further, the current-rush on changing from one speed to another is excessive unless the additional complication of inserting resistance in the primary circuit before changing to the next speed and then cutting it out again, is introduced. Also, the power factor on the lower speeds is very poor and the air-gap may be reduced unduly in order to improve this power factor. Consider now the a.c. commutator motor which has been developed during the past few years. We have the series type and the shunt type. The former is suitable only where the load is constant at each speed, and thus meets only a limited number of requirements. The shunt type should be more correctly called the type having a characteristic similar to the d.c. shunt motor. The motor is made in this country, and the increasing demand shows that it is meeting the requirements for a true variable-speed a.c. motor comparable with the d.c. shunt motor. Its construction is simple, and the commutator requires to deal with only a small proportion of the power of the motor. It is usually constructed for speed-ranges of 3 : 1, but for sizes below 100 h.p. considerably greater speed-ranges can be given, and in this respect the motor is actually superior to the d.c. shunt motor. The important point, however, is that between the lowest speed and the highest speed any desired speed can be obtained, and this cannot be obtained with the change-pole motor. The a.c. commutator motor is even superior to the d.c. shunt motor in this respect, as the speeds of the d.c. motor are dependent on the grading of the field rheostat, whereas the a.c. motor gives the equivalent of a d.c. motor with an infinite number of rheostat contacts between the limits of the speed-range. Further, no rheostat or controller is necessary with the a.c. commutator motor, and it is only necessary to provide a starting switch. The starting current is about equal to full-load current and the starting torque is from one to two times full-load torque. Further, by the insertion of resistance it is possible to get extremely low crawling speeds, and at these speeds the motor is far more stable than the ordinary induction motor. The power factor at the higher speeds is unity, or even leading, and can be maintained at a high value at fractional loads. At low speeds the power factor can also be maintained at a fairly high value. These features of the a.c. commutator motor are sufficient to show that in it we have a motor equal to the d.c. shunt motor and capable of meeting all the requirements for sizes up to from 150 to 300 h.p., according to the speed-range and the frequency. The a.c. commutator motor has not yet been developed to the sizes required for large rolling-mill work, but the multi-speed change-pole motor is quite unsuitable for large reversing rolling mills or modern continuous mills. For the latest type of continuous mill, several of which have been recently installed in this country, the demand is again for a large number of speeds of the order of 17 to 31, and the powers are as large as 4 000 h.p. Such requirements with an a.c. supply are best met by the induction motor working in series with an a.c. commutator motor of the Scherbius type. For small speed-ranges the speed is varied from synchronism downwards, and for larger speed-ranges the speed is varied both above and below synchronous speed. Apart from rolling mills and similar heavy duty, variable-speed motors are required mainly for paper making, paper printing, reciprocating pumps, compressors, fans, calenders for paper and textiles, rubber manufacture, stokers, machine tools and certain special textile work such as calico printing and cotton spinning. The different speeds are demanded by the variation in the class of work with the same machine, and, in addition, the variation of the quality of the materials with the same class of work. The variation in the class of work demands a large speed-range and as large a number of speeds as possible in that range. A variation in the quality of the material demands a temporary or occasional slight change in speed from the customary speed for that work. It is evident, therefore, that, with the exception of large rolling-mill work and other heavy duty, the variable-speed a.c. commutator motor with the shunt-type characteristic and its gradual change from one speed to another, fulfils the requirements of industry for medium-to small-size variable-speed a.c. motors far better than any change-pole motor.

[Mr. Creedy's reply to this discussion will be found on page 333.]

## NORTH MIDLAND CENTRE, AT LEEDS, 9 JANUARY, 1923.

**Mr. J. C. B. Ingleby :** In connection with Fig. 17 I do not quite understand which peaks are supposed to represent the five speeds for the 8, 10, 12, 14, and 16-pole machines, or why the lower no-load currents fall so considerably. Can the author say why, for any given speed shown in Fig. 22, the leakages differ? For instance, taking the 10-pole machine, the leakage is 1·1 on the top curve and 1·82 on the bottom. Referring to the curve of costs shown on the slide, it appears that the difference in price compared with the slip-ring motor varies from 50 per cent to 100 per cent. Does that increase of cost include a starter and transformer, or is it for the motor only? The author's motors will effect a great saving in copper, and it should be commercially practicable to put them on the market.

**Mr. W. B. Woodhouse :** It would, I think, be useful to have a comparison of this particular type of motor with the other alternating-current motors that may be used. First, in respect of the efficiency at different speeds, if the author could give, for example, the relative efficiencies, at various speeds, of a Creedy motor as compared with a slip-ring motor, where the speed regulation is obtained by resistance in the rotor, and as compared with any recognized type of commutator motor, I think that the advantage of the Creedy motor would be more evident. It is a great advantage to have a stable speed which is some percentage of the highest speed. Where the speed of a slip-ring motor is regulated by rotor resistance, one remembers that the speed is not stable if the load varies. I think it would be useful also if we could have a similar comparison for the torques of these different types of machine at different speeds. A machine in which the torque varies with the speed may suit one purpose. In other cases constant torque at all speeds is wanted, or the highest torque is required at the lowest speed. The second half of the lecture dealing with the cascade synchronous motor is particularly interesting to a supply engineer; it seems that we have at last got a motor which not only does not draw any magnetizing current from the line but actually returns some.

[Mr. Creedy's reply to this discussion will be found on page 333.]

## SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 10 JANUARY, 1923.

**Mr. R. A. Chattock :** The introduction of a reliable and simple alternating-current motor having variable-speed characteristics would go far to eliminate the necessity for using direct current for many purposes. The author's description of the multi-speed cascade motor appears to cover all the requirements under ordinary working conditions, and the only questions to decide are whether this type of machine has been run in commercial service sufficiently long to show that it is reliable, and whether the large number of terminals and connections involved proves to be a source of weakness. I should be glad if the author would give some information on this point. The description of the variable-speed induction motor makes it clear that in order to change the speed it is necessary to break the main circuit. I consider that this would prove a disadvantage under many conditions of service. I should also like to know how this interruption of the circuit affects the variable-speed synchronous induction motor, because it seems to me that when the circuit of a synchronous motor is interrupted, it will at once fall out of step and will have to be re-synchronized. Such an operation would in most cases prove to be quite unworkable in practice. From Fig. 21 it appears that the power factor of the variable-speed induction motor is poor compared with that of the ordinary induction motor, and this is especially so at low speeds. This, of course, adversely affects the system of the undertaking supplying the power. I should like to know whether the phase converter to which the author referred as being necessary in connection with the variable-speed induction motor, still further reduces the power factor below the values given in Fig. 21. Has the author tried using condensers or power-factor correctors in connection with these motors, and if so, with what result?

**Dr. M. L. Kahn :** The lecture shows what able and ingenious engineers can do if they set out to satisfy a long-standing demand for special features of machinery, which has hitherto not been met. The author himself appears to recognize the limitation of his invention and states the various cases where a commutator motor is preferable to his propositions. The inherent limitation of his motors is the fact that only a limited number of speeds with rather big steps can be supplied. The limits of 19 r.p.m. and 21 r.p.m. compared with 20 r.p.m. mentioned in the lecture in connection with this point are rather optimistic. As Fig. 21 shows, the step may be 20 to 30 per cent for the most favourable and, incidentally, very costly arrangement, to from 30 to 50 per cent in ordinary cases. Even this is, however, a great advance on the old pole-changing methods where, with one winding only, a speed-ratio of 1 to 2, or 100 per cent stepping, could be obtained. In explaining his winding the author starts from the ring winding with a number of tappings for various numbers of poles, and mentions that similar results could be obtained with a lap-wound drum winding. He does not mention how his winding is arranged. Are we to take it that he also uses lap-wound drum windings in his machines? If so, how is the difficulty of the pole-span of the coils overcome? Normally, coils are wound with a coil-span of about one pole-pitch. They may be lengthened or shortened up to 33 per cent without the output of the machine being materially affected. This means that a winding with a span corresponding to a pole-pitch of 8 poles can be used for 6 poles or 10 poles. For 6 poles the pitch is 0·75 times full pitch and for 10 poles 1·25 times. If, however, the same winding is to be used for a speed-range of 428/1 000, i.e. for 6 poles and 14 poles, as mentioned on page 316, it would, if wound for a mean pitch, have a span differing by 40 per cent from the normal value of the two limits of the speed-range. This will tend to reduce the output obtainable from a given size of machine for the extreme limits of the speed-range. The proposed method of pole-changing involves a motor with a large number of connections, leads and terminals, a phase transformer with similar leads and terminals, complicated switchgear and a starting resistance or auto-transformer. These complications can be justified only in cases where speed variation is absolutely necessary. The claim of increased starting torque for squirrel-cage motors of this pattern can only relate to such cases. The motor cannot supersede the standard slip-ring motor on the plea that it dispenses with slip-rings, while giving at the same time a large starting torque. The complications introduced by the gear and the increased possibility of breakdowns, apart from the question of first cost, far outweigh the advantage of doing away with slip-rings.

**Mr. G. M. Harvey :** I have recently seen some test sheets concerning 10-h.p. single-speed Hunt cascade motors running at 500 r.p.m., and I note that the power factor obtained upon full load is only 0·74. We have at the University a two-speed cascade motor giving 10 h.p. at 750 r.p.m. (8 poles) and 6·6 h.p. at 500 r.p.m. (12 poles) ; the power factors obtained upon test with this motor at full load are 0·86 at the top speed and 0·68 at the lower speed. These figures do not at all agree with those claimed by the makers in some of the earlier papers describing this motor, and I recollect a description of a 300-b.h.p. motor running at 360 r.p.m. with a power factor of 0·92, and giving 200 b.h.p. at 250 r.p.m. with a power factor of 0·9. I should be glad if the author would explain the discrepancy between these figures. I have also noticed in the motor at the University a tendency to stick in the top speed when an attempt is made to reduce to the lower speed by opening the rotor circuit and closing the tapping controller. Can the author explain this ? I am greatly in favour of the cascade motor for mining, and I should be glad if the author would indicate where a simple explanation of the windings of the Hunt cascade motor is to be found. The advantages of the cascade motor for mining work are as follows : The even torque obtained at " crawling " speeds is of great advantage for haulage work, as it prevents " snatching " at the rope. The starting characteristics of a slip-ring motor are obtained without the danger and inconvenience of the use of slip-rings, and a low-speed motor is obtained which compares very favourably in bulk with a plain induction motor running at the same speed. In this connection it seems to me that the advantage claimed by the author for recent improvements which enable the cascade motor to be run at 1 000 r.p.m. are illusory, since the chief advantage is the exceedingly low speed which can be obtained with a reasonable efficiency.

**Mr. F. W. Close :** I appreciate the ingenious way in which the author has made possible the simplification of the control gear by reducing the number of connections which have to be interchanged for the respective speeds. It may be thought that the time required to make the necessary changes in interconnections between the supply, motor and transformer of a six-speed set would be somewhat lengthy, and so allow the motor appreciably to fall in speed during the change period ; but, taking the controller illustrated in Fig. 15, the total time for a change-over on that controller from one speed combination to the next is practically determined by the natural speed at which the contactors will open and reclose, and it is found that the change can be made in something like ½ second, which is about one-quarter the time mentioned by the author. This period of time is an important consideration as, during a part of the time taken to change over, the supply is cut off from the motor, and the latter will therefore commence to fall in speed. With regard to the control of a machine tool driven by a three-speed motor, and the quite reasonable fear expressed that the operator may move the handle in anything but an ideal manner, I have seen in operation the three-speed motor and the controller which the author exhibited. The motor was connected by belt to another machine, and the controller handle was rotated rapidly from the " off " to the " full speed " position, and then back again many times in rapid succession, without pausing in the intermediate steps. No trouble arose, the only thing to be noted being the squealing of the belt due to the rapid acceleration produced by the torque exerted.

**Mr. W. J. Line :** In the lecture the author's multi-speed system is shown applied to polyphase motors. Judging by his silence on the point, he has not entertained the possibility of applying it to single-phase induction motors, or, at any rate, motors running off single-phase supplies, and proposes to abandon this case to the single-phase commutator type. As the elimination of the commutator is admittedly an advantage, giving a simpler and more robust machine, I have a suggestion to make which might enable the advantages of the author's system to be obtained on single-phase supplies also, and the same principle developed on polyphase supplies might enable the transformer, which the author finds necessary, to be replaced by other apparatus which might be cheaper. Consider first the single-phase induction motor running on single-phase mains. The mains and the stator winding may be

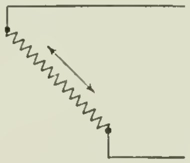


FIG. B.

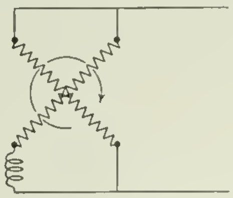


FIG. C.

represented as in Fig. B. For starting, another winding is provided which, either due to its own additional reactance or to a separate choking coil, carries current out of phase with that in the other winding, producing a rotating field instead of an oscillating one (see Fig. C). The same result might be obtained by a condenser in one of the windings, and we might advantageously combine the two, thus causing the current to lead in one winding and lag in the other (see Fig. D). If this were made a permanent running arrangement, a two-phase motor could be run off a single-phase supply. On similar principles a three-phase motor could be run off a single-phase supply as shown in Fig. E, and this arrangement has been used, under certain circumstances, on the Continent. We can add a second three-phase star winding on the same motor, and thus obtain a *six-phase* machine running off a single-phase supply (see Fig. F). The same may be represented in mesh connection, as shown in Fig. G. By connecting those phases which are at 180° with one another, in series and mutually reversed, the number of terminals may be halved, while the machine remains six-phase, and a second speed, double or half the other, might be obtained by the author's methods. Let us now consider motors on three-phase supplies. A six-phase star-connected motor may be run off a three-phase supply (see Fig. H) or in mesh form (see Fig. J), and a nine-phase mesh-connected motor may be run off a three-phase supply in a similar manner, as shown in Fig. K. An arrangement has now been arrived at in which the arrangement of stator winding with 9 terminals, shown in Fig. 7 of the paper, might be utilized. In place of the special transformers required to supply such a winding, three condensers and three choking coils would be required, but the author's switching arrangements would remain unaltered. The question then arises as to whether the condensers and choking coils would be cheaper than the transformer and equally good. Has the author made any experiments in this direction? It is true, as stated in his verbal reply to the discussion, that the leading and lagging effect would not be constant at all loads. Means might, however, be found to overcome this difficulty if the arrangement proved worth while on the score of cost. This point seems worthy of investigation.

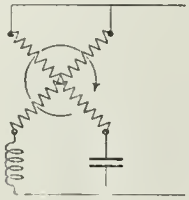


Fig. D.

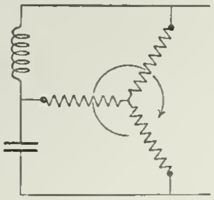


Fig. E.

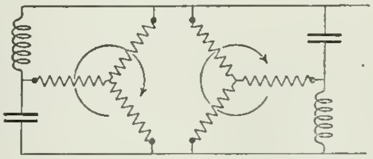


Fig. F.

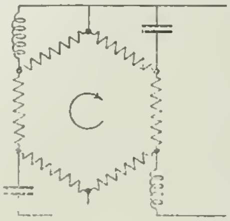


Fig. G.

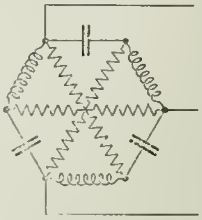


Fig. H.

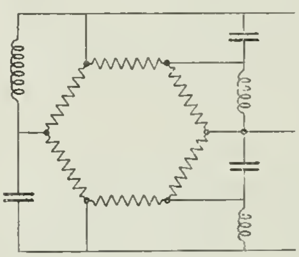


Fig. J.

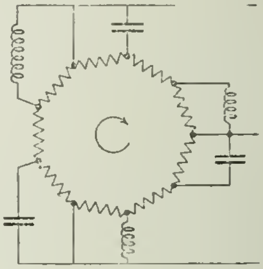


Fig. K.

[Mr. Creedy's reply to this discussion will be found on page 333.]

## North-Eastern Centre, at Newcastle, 22 January, 1923.

**Mr. F. H. Downie:** The author has given a most interesting account of a new development in induction motors, which will have many applications in practice. Can he give some information about the variation in the breadth factor with the different numbers of poles? In the existing two-speed windings of Lindström, for example, the breadth factor is 0·95 for the larger number of poles and 0·7 for the smaller number, showing that the winding is not equally efficient in both cases. I should like to know if a similar result is found in the case of the windings described in the lecture. Usually these windings for different numbers of poles show harmonics in the field distribution curve, the seventh especially reaching high values which produce a tendency for the motor to crawl at one-seventh synchronous speed when a squirrel-cage motor is started. Has the author found similar effects in motors with the winding described? Are there any limitations to the possible numbers of poles for which a motor can be wound? In other words, would it be possible to wind a motor for 20, 22, 24, 26, 28 and 30 poles, thus giving 6 speeds covering a range from 300 r.p.m. to 200 r.p.m. with a 50-period supply? Fig. 18 leads me to expect that the ratio of maximum torque to normal torque varies with the number of poles. Is it possible to design a motor to have a good power factor and efficiency at all speeds and at the same time a ratio of maximum torque to normal torque of at least 2 at all speeds? The author mentions that in Fig. 18 the torque represented by 1 mm is proportional to the number of poles, and from this I gather that the maximum flux density in the gap is constant at all speeds. I should like the author to confirm this. I think that the polyphase commutator motor has a greater field of usefulness than the author would leave to it, and that for small outputs it would in many cases be cheaper and better to use a commutator motor than a variable-speed induction motor.

**Mr. J. W. Jackson:** From my early experience with this particular type of motor plant I found that I was developing bias against it because of its apparent unreliability. This, however, I afterwards found to be not so much a charge to be levelled against the technical arrangements of the equipment, or even the manner in which it had been manufactured, but rather the commercial arrangements of the manufacturer were at fault in dealing with the breakdowns when they did occur. Breakdowns are bad enough, but when added to these there is a serious difficulty in effecting repairs, no one can wonder at a plant gaining a bad reputation. I should like the author to explain why the motor takes a greater amount of current when running at its lowest speed and no load, than it does when it is running at its highest speed and no load. Is this low-speed arrangement secured at the expense of power factor? During the past two years I have had personal experience with motors having four-speed and six-speed arrangements, one of these being of the earliest pattern and fitted with the popularly described "piano" type of controller. All these have been remarkably free from trouble. It would appear from the lecture that the cascade type of motor would very quickly repay the increased capital cost over a fixed-speed motor when applied to air compressors, from which very frequently a small amount of work is required. When the fixed-speed motor is fitted, a large percentage of the full power is used on the compressor even when it is delivering a small amount of power, thus giving an extremely low efficiency, or, in other words, increasing very considerably the power costs for air-compressing. There is apparently a strong feeling that the cascade motor is not as reliable in operation as a fixed-speed motor, and when added to that idea of unreliability is that of the considerably increased capital cost, it is not surprising that the fixed-speed motor is installed.

**Mr. A. T. Robertson:** There is a great deal that requires explanation before the subject can be clearly understood, particularly in regard to the details of the windings employed; for instance, no indication is given by the author as to how he obtains the equivalent of the ring winding with a winding of the usual drum type. Is it correct to assume that the drum winding used has such a pitch as to give the smallest number of poles required in any particular case? Where only two-phase supply is available does the author propose to convert this by means of the phase transformers to the same number of phases as would be used if three-phase supply were available, and so use similar machines for both two-phase and three-phase supply? There will not be the same possibility of convenient speed-ranges on 40 and 25 periods as given in the lecture for 50 periods, and it would appear that commutator motors might be necessary, particularly on 25 periods, whereas a pole-changing motor could be used on 50 periods. On page 315 it is stated that the size of the phase transformer may be reduced from 30–40 per cent of the size of a voltage transformer for the same power, to 18–20 per cent when using the factor 0·75; these figures appear, however, to require some modification. The analogy of the automobile gear is most unfortunate, as the whole point is that a constant-torque, not constant-power, electric motor is being considered, whereas the automobile engine is a constant-power unit, the gear being used to obtain higher torques at low speeds. Direct drive on top gear is used, so that the most efficient drive is obtained for normal running.

**Mr. C. Turnbull:** We are the more indebted to the author in that the information given in the lecture might prevent him from taking out a valuable patent later. The day may come when Parliament will realize that the penalizing of inventors by annulling a patent on the plea that the idea was more or less vaguely foreshadowed in a scientific paper, is not beneficial to the nation. The difficulty with variable-speed motors is that the variations required do not always fit in with those obtainable by the author's methods. Are the motors in question suitable for printing-machines, lifts and organ blowers?

**Professor W. M. Thornton:** Is there any upper or lower limit to the sizes of the motors? For example, could one use them efficiently up to 10 000 h.p. for rolling mills, and as low as 1 h.p. for organ-blowing? Is there a size in which the efficiency of construction and operation is a maximum, due regard being paid to cost?

## THE AUTHOR'S REPLY TO THE DISCUSSION AT LONDON, LEEDS, BIRMINGHAM AND NEWCASTLE.

**Mr. F. Creedy** (*in reply*): I have to thank Mr. Hunt for his very clear exposition of the principles of the multi-speed winding described in Part I of the lecture, and its relation to both the old and the new cascade windings. I am quite in accordance with his views. The data which he gives of the relative d.c. and a.c. ampere-turns on the synchronous cascade motor, and also those relating to large ship-propulsion motors, are very interesting. I myself have found it necessary to use three groups of coils per pole instead of three groups per pole pair in designing such a multi-speed motor as he refers to, and have found a similar improvement in its properties.

I have also to thank Dr. Smith for his alternative statement of the principles involved. All such alternatives are of value, as one view point may appeal more than another to any given individual.

Mr. Jack, in his remarks, has scarcely been fair to alternative types of apparatus. It is quite true that for the past 15 or 20 years it has been possible on known principles to build 2-, 3- or 4-speed change-pole motors, but Mr. Jack does not point out that a 2-speed motor, if with a single winding, could only have speeds in the ratio of 2–1, that is, 100 per cent stepping. To obtain anything better than this, two distinct windings must be employed. The disadvantages of such windings are very great in many cases, as they involve a much larger frame size, very much impaired ventilation, and much greater magnetic leakage. If I were to permit myself the use of two windings in this manner, I could obtain a 12-speed motor with a speed stepping of 10–15 per cent. Without using the two windings and employing a type of design which permits us to obtain, from a given frame size, about 85 per cent of the output given by a single-speed motor, a step of 20 per cent in the most favourable case and 30 per cent in ordinary cases can be obtained, as pointed out by Dr. Kahn in the discussion at Birmingham.

It does not appear to be sufficiently realized that in these multi-speed motors any combination of numbers of poles can be obtained whenever it is worth while to do so, and, while dealing with this point, I may reply to Mr. Downie's remarks on the same subject in the Newcastle discussion. It would be quite possible to obtain such a combination as 20–22–24–26–28–30 poles in large machines. It would involve a 3–24 phase transformer and controller similar to that shown in Fig. 15, but having 12 instead of 9 switches on each vertical shaft.

Another difficulty of the old multi-speed motor was the practical impossibility of building it with slip-ring control. This difficulty also has been remedied by the new winding, thus adding very much to the field of application of the machine.

Mr. Jack does not, I think, improve his case by complaining that there are no speeds available from 1 500 r.p.m. to 750 r.p.m. on 25 periods. Small 25-period motors certainly offer a better case for the commutator machine than on any other frequency, although, even here, machines of the multi-speed type running at speeds of 750/500/375 have been used with success down to fairly small sizes. Probably more motors have been built for 40 periods than for any other frequency, and there can be no question that the machine forms a very useful piece of apparatus at this frequency.

The power factor of the machine is discussed in connection with remarks made by other speakers.

I do not, of course, claim that the multi-speed machine is the only type of variable-speed apparatus that should ever be used, and this is, I believe, made sufficiently clear in the lecture. On the contrary, it is this very attitude that I protest against, namely, that of making a hobby of a particular type of apparatus and trying to apply it whether or not it is the most suitable for the purpose. If in any given case the commutator machine is really the best, I hope I shall be the first to recommend it. On the one hand, for instance, we have the continuously variable speed, which is certainly a very strong point, while on the other we have to content ourselves with speed-steps of the order mentioned above. By means of these speed-steps we can in any given case get within 10 per cent or, at the most 15 per cent, of the speeds desired. For instance, supposing we wish to obtain a speed of 875 r.p.m., the nearest we can obtain is either 1 000 or 750 r.p.m., each of which differs from the speed required by 12½ per cent. We have first to settle, therefore, whether a speed variation of 12½ per cent from the ideal value causes any serious detriment. Next, we have the lower efficiency of the commutator machine, amounting to approximately 10 per cent, as may be seen by reference to Mr. Teago's paper,* which shows that the efficiency of a 10 h.p. motor does not exceed 80 per cent, as against well over 90 per cent in the case of an induction motor. The effect of this on running costs cannot be ignored. For instance, in a 25 h.p. motor running 8 hours a day and 5½ days a week, a machine with 90 per cent efficiency takes 1 000 units less a quarter than the machine with only 80 per cent efficiency. On the other hand, it is only fair to say that the commutator motor on some of its speeds, though not all, gives a better power factor than the induction motor. This may somewhat offset the lower efficiency in cases where a system of charging is adopted which takes account of the power factor.

Having settled these two points, we have next to consider whether the motor can be built to give the speed-range desired. Owing to the requirements of commutation, the flux per pole of a variable-speed commutator motor is strictly limited, and consequently motors of considerable size must have a large number of poles, i.e. they must be built for a low speed. The multi-speed type of motor is not subject to any such limitation and can, on the contrary, be built for nearly any speed-range desired on normal frequencies, although, as stated above, the case for the commutator machine is certainly improved on 25 periods.

I quite agree with Mr. Jack that the modern a.c. commutator motor can be built so as to be free from commutator and brush troubles. Another point which really cannot be lost sight of is that of first cost, to which he makes no allusion at all. In large horse-powers, owing to the necessarily very low speed of the motor and its extremely large commutator, this cost must be very high, and it is just here that the multi-speed motor shows to such advantage, since it can be built for almost any speed. The greater the size, the smaller in comparison is the cost of the switchgear. In small sizes the commutator motor is more favourable, while the switchgear of the multi-speed type tends to become expensive relative to the machine itself. Hence, we are practically restricted to the simpler three- or four-speed types below, say, 10 h.p.

Fig. 14 shows the relative costs of the multi-speed motor and it would be interesting if, on some other occasion, a similar curve relating to the commutator motor could be published. In some cases I am aware that the advantages of the continuous speed-range are so great that all the above questions must be answered in favour of the commutator machine.

With regard to the use of multi-speed motors for rolling mills, I have devoted a good deal of attention to this subject also, and a type of motor is now being considered in which an absolutely gradual speed variation can be obtained entirely without the use of commutating machinery. I hope to be able to publish further particulars of this on a future occasion.

---

* *Journal I.E.E.*, 1922, vol. 60, p. 328.

Confining ourselves to familiar apparatus, however, it is well known that the size of a cascade commutator set of the Scherbius or Kramer type such as those advocated by Mr. Jack is proportional to the difference between the speed of the main induction motor and its synchronous speed. If, therefore, we can use a multi-speed motor such as that shown in Fig. 7, which is capable of giving, say, three speeds with slip-ring control on each, we can reduce the size of the auxiliary set to a mere fraction of that required if the main motor is of the single-speed type. Hence, even where continuous speed variation is required, the multi-speed motor enables us to effect great economies. In point of fact, in merchant mills, where speed-change is required principally when changing the section to be rolled, continuous speed variation is in no way necessary, and the multi-speed motor as described in the lecture is by far the most economical apparatus that can be installed, both as regards first cost and cost of operation.

In view of the examples of rolling-mill motors now actually in operation and referred to in the lecture, I cannot understand how Mr. Jack can assert that these machines are not suitable for rolling-mill work.

In replying to Mr. Chattock's remarks in regard to power factor, I propose to deal with those of other speakers on the same subject. The full-load power factor of the machine varies, being on top speed quite as high as, or in some cases higher than, in the best induction motors, owing to the multi-speed motor having a far greater number of phases per pole than the ordinary three-phase motor, which leads to a wave-form approaching a sine type much more closely than in the latter. This is dealt with more fully below. The power factor falls off as the speed decreases, due to the reduced horse-power output of the motor. The amount of wattless current absorbed by the machine is, however, practically constant and it is this, and not the power factor directly, which is of interest.

A multi-speed motor giving 100 h.p. on its top speed and therefore rated as a 100 h.p. motor will take practically the same amount of wattless current as a 100 h.p. motor arranged for one speed only. When it is only giving 50 h.p., due to the reduction of speed to one-half, it still continues to absorb the same wattless current, and consequently gives the same power factor as a 100 h.p. single-speed motor when running on half load.

Dealing with the question of phase compensation, it has not yet been found possible to apply phase compensation on this type of motor on more than one of its speeds. As mentioned in the lecture, it can be made to operate as a synchronous motor on two speeds, but arrangements having a suitable degree of simplicity have not been developed on these lines for more than two, or possibly three, speeds.

It may here be stated that these multi-speed synchronous motors are self-synchronizing on each speed. Some machines have been built which will synchronize themselves when switched in at a speed of 10 per cent below synchronism, although this is, of course, not recommended, but no difficulty whatever is experienced if the machine is allowed to run up as an induction machine and the exciter circuit then closed.

Due to the fact that the amount of wattless current taken on all speeds is practically the same, however, the static condenser presents an ideal method of raising the power factor of such a set to unity, and, wherever this requirement is met, it is usual to connect the static condenser in parallel with the set, when it will raise the power factor to unity on every speed, and not on one only, and keep it above 0·95 on practically every load.

In reply to Dr. Kahn, Mr. Downie and Mr. Robertson, I have apparently not succeeded in explaining sufficiently clearly how it is that a lap-wound drum winding can be used instead of a ring winding. Fig. L shows three sketches of a drum-wound coil lying (*a*) in a field of six poles, (*b*) in a field of 10 poles and (*c*) in a field of 16 poles, the pitch of the coil being approximately one-tenth of the circumference. The sine curve shown in the figure may be taken to represent the values of the air-gap density at a particular instant and, if so, the ordinate AB to the curve will represent on a suitable scale the voltage induced in the left-hand conductor. Similarly, the ordinate CD represents that induced in the right-hand conductor. The curves have in every case been so drawn that the left-hand conductor lies at the point of maximum density. The total E.M.F. induced in the coil will in each case be (AB + CD). It will be seen that in curve (*b*) (Fig. L), representing the 10-pole condition, the E.M.F. induced in the coil is a maximum, since CD as well as AB is a maximum. In the curve corresponding to six poles, the pitch of the coil is considerably less than the pole-pitch and, therefore, CD is a good deal less than AB, but nevertheless the sum of the two is only reduced to about 70 per cent of its previous value. Similarly, in curve (*c*), representing 16 poles, the pitch of the coil is a good deal more

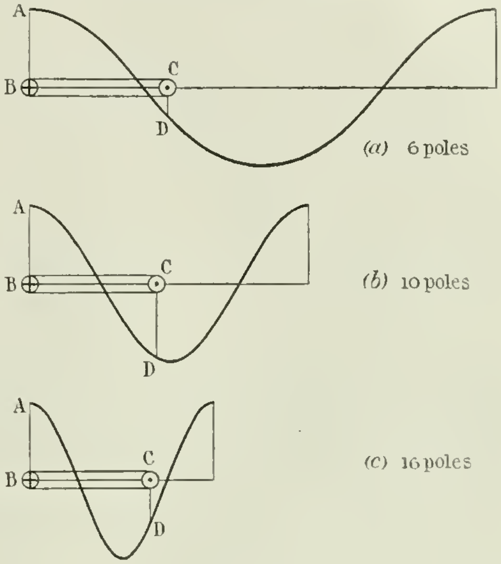


Fig. L.

than the pole-pitch and therefore CD is again reduced, but again the sum of AB and CD is only about 70 per cent of its full value. It is, in fact, in order to prevent too great a difference between the pitch of the coil and the pole-pitch, that it is usual to limit the speed-range of these motors to a value not exceeding 3–1.

I should like here to clear up a slight misunderstanding into which several speakers appear to have fallen. It is only the cascade machine that I consider to be suitable for use as a single-speed machine, and I agree perfectly with Dr. Kahn that the control gear required with the multi-speed machine is too elaborate to allow it to be used as a one-speed machine.

In reply to Mr. Harvey, I am not sufficiently conversant with the history of the cascade motor to enable me to answer his remarks as regards the machines of which he has had experience, as it is only comparatively recently that I have become connected with this type of machine.

It is a normal characteristic of the cascade motor as hitherto built, that if brought up to its top speed by any means, as, for instance, by the short-circuiting of the slip-rings, it will continue to run at that speed, notwithstanding the fact that the slip-rings are again open-circuited. This is also true of the cascade set, for instance the set shown in Fig. 23. If the first machine is brought up to its synchronous speed, 1 000 r.p.m., the rotor frequency is reduced to zero or, at most, $\frac{1}{2}$ period per second. At such a frequency as this practically no voltage will be induced in the secondary of the second machine, which accordingly carries little or no current. The primary at a frequency of $\frac{1}{2}$ period has extremely little inductance and acts almost purely as a resistance in series with the slip-rings of the main motor. This is, I think, the explanation of the characteristic noticed by Mr. Harvey, which is common to all cascade apparatus whether internally or externally cascaded.

I regret to say there is really no elementary exposition of the principles of the internal cascade motor, and I can only refer once again to my previous paper.* Mr. Harvey states that for mining work the low-speed cascade motor meets all requirements, but the properties of the cascade motor are available far beyond the mining field and it is in this extended field that high-speed motors show to their greatest advantage.

It is largely due to Mr. Close's design of controller, namely, that shown in Fig. 15, that this type of machine, at any rate in the larger sizes, has assumed a practical form. Other types of controller have been used, notably one which became popularly known as the "piano" type and which is referred to by another speaker, but it was not until the controller shown in Fig. 15 was designed that I felt that all the problems had been really solved. Mr. Close's confirmation of my statements in regard to the time required to change speed with the type of controller shown in Fig. 15 is very welcome. This should be sufficient to answer Mr. Chattock's inquiry as regards any possible difficulty due to this case. In none of the considerable number of these machines which have been placed in service, many of them starting and changing speed under full load, has any difficulty of this nature been experienced.

In reply to Mr. Line, I have not considered it desirable to use these multi-speed motors on single-phase circuits. I hold rather strong views on this subject, although the present is not the place to enlarge on them, and I believe that the single-phase induction motor is at the present moment entirely obsolete and that within a very few years it will cease to be marketed, its place being completely taken by the commutator motor. Without discussing Mr. Line's various arrangements in detail, it seems to me that they would be vastly more expensive than the simple type of transformer which I employ.

Mr. Ingleby draws attention to a number of points in which the lecture is not perfectly clear. Dealing with these points in order, the point 1/2 in Fig. 17 marks a point at which the number of poles is changed from 16 to 14. The sequence of operations is as follows :—

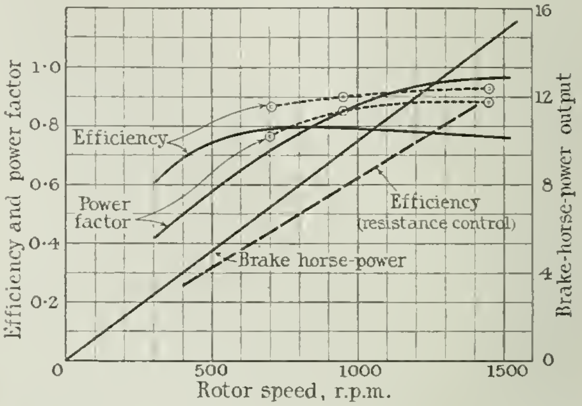


FIG. M.—Torque maintained constant while speed was varied by brush adjustment, by pole changing, or by altering rotor resistance.

Simultaneously with the change in the number of poles, the voltage is reduced by means of an auto-transformer tap on the controller, in order to reduce the current kick. This explains the reduction in the no-load current after the change in the number of poles. The second step in the controller, namely, that marked 2/3, restores the voltage to its normal value, and it will be seen that the no-load current shows a considerable rise. Similarly, the point marked 3/4 corresponds to the change from 14 to 12, 5/6 from 12 to 10 and 7/8 from 10 to 8. The leakage coefficients differ in the curve shown in Fig. 22, because these three curves relate to different machines.

The cost curve gives the ratio of costs between the slip-ring motor complete with its starting panel, circuit breaker, etc., and the multi-speed motor complete with its switchgear, circuit breaker and transformer (where necessary).

As requested by Mr. Woodhouse, I have included in Fig. M a curve showing the relative efficiencies of the multi-speed motor and the motor regulated by resistance control. Another curve shows the relative efficiencies of this motor compared with the Schrage commutator type of motor, the efficiencies of the latter being taken from Mr. Teago's paper already referred to.

---

* *Journal I.E.E.*, 1921, vol. 59, p. 511.

In reply to Mr. Downie in regard to harmonics, the number of sections per pole is greater than on a two-phase motor, even at the lowest speed. On the higher speeds, however, the number of sections per pole is far greater than in even the best types of three-phase motor, the consequence being that the wave-form on the higher speeds approaches the pure sine curve more closely than in any standard three-phase motor, the deviations from it amounting to less than 2 per cent, as shown by the diagram drawn after the manner explained by Hellmund.* This has a marked effect in improving the power factor and it is found that exceptionally high power factors are obtained on the higher speeds of these machines.

I have never noticed any tendency for the machine to crawl at one-seventh full-load speed. This is an extremely annoying tendency in the single-speed squirrel-cage motor, and while it might conceivably occur in a multi-speed motor connected for, say, its lowest speed, we have a ready means of eliminating it by merely switching the motor on to another speed, so that such a cause of trouble, should it occur, is by no means so serious with the multi-speed type.

It is quite true that the ratio of maximum torque to normal torque varies with the number of poles. I endeavour to allow a ratio of maximum to full-load torque of not less than 1·8 on the minimum speed, rising to about 3·5 on the top speed. Again, as mentioned above, where a motor is subjected to an exceptionally heavy load on one of its low speeds so that the slip is great and the danger of pulling-out considerable, it is quite easy to switch it on to the next higher speed; hence again we have resources which do not exist in the single-speed motor.

It is quite true also that the maximum flux density in the gap is approximately constant at all speeds. Mr. Jackson's remarks are very interesting, as coming from one who has large actual experience with this type of motor. As a matter of fact, the first machine of this type ever built, referred to on page 312, which had none of the later improvements, and therefore required a transformer having no less than 30 phases has, I believe, been under Mr. Jackson's care. This machine is fitted with the very elaborate "piano" type controller that he refers to, and when first installed it required a good deal of adjustment. Even these earlier elaborate motors have, however, now run for several years without, I believe, requiring any attention, and from the later ones containing the simplifications described in the paper which permit of the use of a drum-type controller, practically all the possible causes of weakness in the earliest type have been removed. These motors are used to operate mechanical stoker gear and are of the squirrel-cage type, being the smallest machines built to give the full six speeds. In order to obtain these results with a minimum of switchgear the motor is of the constant horse-power type, in which the flux is reduced as the speed is raised, more or less as in the d.c. machine. This involves a corresponding reduction of the magnetizing current, and this is the explanation of the high magnetizing current noticed by Mr. Jackson.

In the modern type the magnetizing current is practically constant at all speeds. I quite agree with Mr. Jackson that there is a great field for this type of machine in connection with air compressors, and automatic control gear is now being developed to enable them to be applied in this direction. Mr. Jackson's views as to the unreliability of the cascade motor seem to me to be quite unique, as my experience is that one of its strongest points is its extreme reliability owing to the very great simplicity of its construction.

In reply to Mr. Robertson, two-phase motors have not been worked out in quite the same fullness of detail as three-phase motors, but on two-phase supplies it is proposed to use as far as possible a special two-phase transformer and a winding with a different number of sections.

As regards the automobile gear, the point is not of great importance, as the analogy is only a very general one. I wished to point out that arrangements are made in the automobile to avoid using gears under the most severe conditions of working, and that I do the same. It is immaterial that the severest working conditions may appear under different circumstances in the two cases.

In reply to Mr. Turnbull, these motors can be readily applied both to printing-machines and lifts. As regards organ-blowers requiring only a 1 h.p. motor or so, I prefer the small commutator type of motor. An organ-blowing equipment can be regarded as an air-compressor plant in miniature, and we find this type of machine admirably adapted for slightly larger plant requiring from 3 h.p. to 5 h.p.

These machines have been designed up to 20 000 h.p. for ship propulsion, while the low limit of rating is about 2 h.p. to 3 h.p.

---

* *Transactions of the American Institute of Electrical Engineers*, 1908, vol. 27, pt. 2, p. 1373.

# WORKS PRODUCTION.

By G. H. Nelson, Member.

(*Paper first received* 19*th December*, 1921, *and in final form* 2*nd March*, 1922; *read before* The Institution 18*th January*, *and before the* North-Western Centre 23*rd January*, 1923, *also informally before the* Sheffield Sub-Centre 21*st December*, 1921.)

## Summary.

During the past two years a great deal has been written about production problems. Some of these contributions to the subject have been penned by idealists, who claim, for instance, that such and such a shop lay-out is the first essential to successful production. Others emphasize that lack of production is caused by "ca' canny" amongst the workers. The bearing of these factors on production, or the lack of it, can be dealt with by efficient organization and management, and it is with the establishment of such a works organization that this paper will deal.

With a view to interesting all sections of the industry, the author has dealt with the subject on general lines, with particular reference in places to the manufacture of electrical machinery, the object being rather to outline a general policy that has been followed in works with which he has been associated, than to go into detail which may not be applicable to any other works, as, naturally, detail must be based on the equipment in a particular works and the design of the apparatus manufactured.

## Introduction.

Those who are continually in close touch with the workers cannot but feel the great responsibility which falls on them in being obliged to discharge men due to shortage of work; and cases occur which bring home to one the necessity of doing everything possible that may influence an improvement in trade. One appreciates that it is not possible to remedy all the defects at once, but if each individual assists in his own particular sphere results will soon be obtained.

The present depression is due mainly to the following four causes:—

(1) Taxes, etc., direct and indirect (necessary to pay for the cost of the wastage of war), which caused higher prices of commodities.

(2) The effect of (1) on the *morale* of the workers, resulting in the forcing up of wages to meet increased prices.

(3) This in turn has caused a further rise in the prices of commodities with a view to meeting these taxes plus increased costs of production.

(4) The accumulative effect of (1), (2) and (3) producing rash speculation, in its very widest sense, and upsetting the whole basis of labour's wages, trading and economic standards.

The remedies are now being applied and everybody must suffer, more or less, in consequence. These come in the reverse order to the causes, thus:—

(1) Traders' rash speculation has been stopped by the limitation of credits.

(2) The cessation of speculators' orders for goods (for which there was no real money available to pay) causes a lack of work.

(3) This, in turn, necessitates economic adjustment of wages and also makes the worker realize that he must give a day's work for a day's pay in order to retain his employment.

(4) Lastly, we come back to the necessity for economy in every direction in order to provide funds to pay off the debt which caused the high taxation; and the liquidation of debt will in time cause taxes to fall.

The nations of the world are poorer, and the present conditions can only be improved by economizing generally and by producing the world's needs more economically and so, even with reduced available income, enabling goods which are necessities to be purchased.

The author fully appreciates that there are other matters (besides reduction of costs of production) that need attention, such as adjustment of exchanges, and the investigation into and reduction of heavy costs of distribution in many industries. These, however, will no doubt be dealt with in time. If every section, i.e finance, manufacture, distribution and labour of all grades, does its best towards this rebuilding of the industrial world, we shall have nothing to fear in the future.

The particular problem with which the author proposes to deal is the basis of production of the best article in the shortest time, at the lowest price. It should be realized, however, that lowest cost does not necessarily mean lowest wages, but it certainly does entail the most economical method of production, by the joint efforts of both employer and employed.

Much has been said and written about so-called "ca' canny" amongst the workmen, but the author is of the opinion from experience that this can be eliminated by a management which looks for and removes the causes and does not simply complain about the results of "ca' canny."

The fundamental for the organization of economical production is co-operation. A shop with a good layout, manufacturing good designs, does not necessarily produce cheap and good articles. There must be the closest co-operation between all sections of the staff and workmen before any real success can be achieved. The basis of co-operation is naturally the human element in all branches of the organization, and the amount by which the ideal is approached is controlled by the results obtained by the weakest human link. This is fundamental, and the author personally considers it to be of first importance. For this reason it is referred to before dealing with questions of general organization. The heads of factories must first be students of human nature, so that in selecting men for executive positions they can satisfy themselves that these men, in addition to thoroughly understanding the technical and practical side of their respective appointments, can also select and lead their subordinates to co-operate with other sections or branches of the works.

The special problem of the manufacture of electrical apparatus is so complex that it really cannot be left to haphazard methods, for there is no apparatus made in which there is a greater variety of materials.

TABLE 1.

*Chart of Number of Parts and Materials used on a Standard Design of Rotary Converter.*

| Description of materials | Number of separate parts used |
|---|---|
| Rolled hard shaft steel | 1 |
| Cast steel | 17 |
| Forged steel | 3 |
| Special low-carbon steel | 1 |
| Mild steel | 93 |
| Key steel | 27 |
| Electrical sheet steel (ordinary quality) | 518 |
| Black sheet steel | 1 529 |
| High-tensile steel wire | 98 |
| Spring steel | 4 |
| Copper-plated spring steel | 48 |
| Cast iron | 38 |
| Wrought iron | 12 |
| Phosphor bronze | 2 |
| Cast brass | 100 |
| Brass rod | 47 |
| Sheet brass | 48 |
| Lead | 5 |
| Bell-metal | 6 |
| Hard-drawn high-conductivity copper bar | 270 |
| Rolled copper bar and strip | 557 |
| Tinned copper strip | 270 |
| Sheet copper | 132 |
| Copper wire | 6 |
| Copper tube | 10 |
| Flexible cable | 8 |
| Carbon | 72 |
| Bakelized micarta | 52 |
| Bakelite | 1 |
| Fibre | 186 |
| Mica | 1 |
| Micanite | 316 |
| Fullerboard | 18 |
| Canvas hose | 2 |
| Hardwood | 78 |
| 9 plywood | 6 |
| *Sub-Total* | 4 582 |
| Steel nuts, bolts, washers and rivets | 1 248 |
| Copper rivets | 576 |
| *Total* | 6 406 |

TABLE 1—*continued.*

*Insulation material.*
5 different qualities or thicknesses of fullerboard.
2 different thicknesses of leather paper.
Fibre.
Torpedo cord.
Bare paper mica.
Micanite strip.
Enamelled rope.
3 different thicknesses of tape.
2 different thicknesses of empire tape.
*Varnishes.*
Mica-sticking varnish.
Clear insulating varnish.
Standard baking-coil varnish.
No. 2 black finishing varnish.
Grey enamel.
Shellac (of 3 different specific gravities).
*Finish on castings.*
Anti-corrosive paint.
Knife filler.
Leather filler.
Brush filler.
Coat of priming paint.
Coat of finishing paint.

Total number of separate parts used (not including nuts, bolts, washers or rivets) = 4 582
Total number of different materials used = 55

In addition to the various ferrous and non-ferrous metals, there are insulating materials, mica, paper, linen, cotton and silk in various forms, string, fibre, asbestos, etc., and numerous varnishes and solvents. These, it will be appreciated, involve the employment of all types of labour, skilled and semi-skilled, in many different trades. Table 1 gives a list of the materials and the number of parts used in a rotary converter.

To achieve success in the manufacture of machinery such as the above on anything like a large scale, the works organization should be subdivided into distinct sections, each section having clearly defined functions. From experience, a works sectionalized as follows has given eminently satisfactory results :—

(1) Design.
(2) Works Superintendence.
(3) Technical Process Department.
(4) Rate-Fixing and Mechanical Process Department.
(5) Production Department.
(6) Inspection Department.
(7) Costing Department.

Fig. 1 shows the relationship between these sections.

These divisions were arrived at in an endeavour to arrange for the efficient automatic application throughout a works of the knowledge and experience of specialists in each particular branch, all co-operating to get final economic manufacture. It is quite impossible to find a man versed in carrying out the detail of all these various branches, and the aim of all manufacturers should be to obtain the full benefit of accumulated specialized experience and to pass this down to the actual worker, so that he can apply his manual effort and skill in the best way. The time is past when a technical business can be run by one man doing everything, including the buying, the works managing, the planning, the costing, etc., and general supervision. This was satisfactory in the past when competition was not keen and the margins of profit were much higher, and when technical knowledge was not developed as it is to-day.

The success in actual practice of introducing the system about to be described is shown by the following results :—

(1) The relation between the total value of the work in progress and the value of the monthly output of completed machines was reduced from 7 months to 4½, thus giving a very considerable saving in capital required and the interest on that surplus capital..

(2) The average time of manufacture of a certain size of machine was reduced from 22 weeks to 18 weeks, and that of other sizes relatively. This has since been still further reduced, but this is accounted for by the fact that the shop is not now fully employed.

(3) The number of machines overdue was reduced two-thirds.

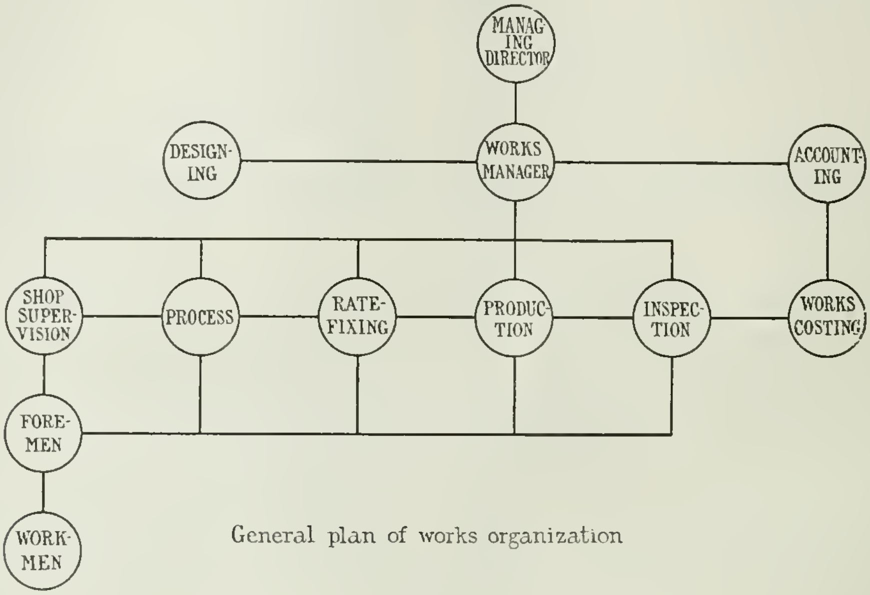
(4) The number of defects arising during manufacture on various operations has been reduced two-thirds.

(5) The accumulative effect has reduced the cost of manufacture by quite a considerable percentage.

The general lines of the system adopted in each of these sections which accomplished the above results will now be dealt with.

### Design.

Under this particular heading the author must again take the opportunity of referring to the question of co-operation, for, in his opinion, unless the experience and knowledge of everybody concerned in the manufacture of a particular product is drawn upon and embodied in the design, the best results cannot be obtained. No man can be an expert in every process and operation in the manufacture of a piece of electrical apparatus. Each particular branch of industry is a large proportion of a life's study, and in large and small works specialists in various directions exist, and it is in the interests of manufacturers to consult them and get their ideas embodied in the design, so that mistakes and delays are not experienced in the shops. The author once heard a remark that one could not expect the people in the works to know the technical details that the designer has in mind, and he is in entire agreement with this. It is important, however, that as much as possible of this information be imparted to the workers. Every effort should be made by designers and shop staff to apply this principle of co-operation in its broadest meaning, and make full use of the knowledge of experts in various shop problems.



General plan of works organization

Fig. 1.

In this connection the author has one very good example in mind of an end bracket made from a 4-part pattern, with intermittent machining surfaces. The same bracket was re-designed for a 2-part pattern, with a consequent saving of 17½ per cent of the total factory cost, due to the simplification of machining and reduction of the number of scrap castings. If the co-operation of a foundry expert and machine expert had been solicited in the early stages, this design would never have been issued to the shop.

The author considers that a design of each part of a piece of apparatus should be considered at a meeting of the designer, the manufacturer and, if necessary, the salesman (who should know the requirements of purchasers) before it is finally put into manufacture, in order that the requirements of each party may be properly embodied.

Particular care should be taken to see that shop drawings are clearly dimensioned and limits of accuracy given. Unmachined, rough machined and finished machined surfaces should be clearly marked.

### WORKS SUPERINTENDENCE.

The most important consideration under this heading is that of labour. In order to handle this problem efficiently all those who have the handling of labour must be satisfied in their own minds that the biggest percentage of workmen are reasonable men, and, if this good percentage have rather distorted ideas on any particular subject, they should not be blamed but helped to change their distorted views. Problems looked at from their limited outlook can easily produce the conclusions at which they arrive. When these conclusions are wrong it is the duty of all employers of labour to endeavour to put before their employees both sides of the problem. The problem then often resolves itself largely into the elimination of selfishness from all parties, employers, employees and employees' unions. The author, personally, has the greatest respect and affection for the working classes as a whole, but he realizes that the vast majority are not in a position, through lack of knowledge, to consider the problems with which they are faced, and therefore simply accept the teachings of loquacious agitators.

(*a*) *Works education.*—The importance to all in industry, and to the nation as a whole, of improving the position is apparent to those in close touch with the workers, and the future can be best taken care of by the proper provision for the training of apprentices. In this training, apart from their ordinary trade, there should be included lectures on economics. How few workmen realize what the secretary of a leading trade union recently pointed out, namely, that 90 per cent of the costs of production is borne, indirectly perhaps but nevertheless borne, by the workers themselves!

The days when an apprentice could be left to his own resources to pick up his trade in the shop have gone. Competition is too keen and it is necessary, in the interests of the men as well as of the manufacturer, that they should be taught on a systematic basis. In the works with which the author is associated in Sheffield there are apprentice classes where the apprentices are given, in the employer's time, lectures by skilled men in the various trades such as fitting, turning and winding, and in addition are given details of the rudiments of rate-fixing and costing, so that they acquire this knowledge in their very early life and are able to consider problems from the broadest point of view. It is hoped that when the apprentices become men they will not have to follow the advice of destructive leaders in trade unions, but will themselves be able to give considered and constructive opinions. The author considers that these lectures, particularly on economic questions, should be extended to the fully-paid workmen, and where they have been given at the Sheffield works he has found that the men take the keenest intelligent interest in the subject.

The author would here like to say a particular word with regard to technically-trained men, i.e. men who take their degrees in engineering. It is essential that our universities and technical schools should include in their curriculum a course of economics. Lectures should also be given on the relation between so-called capital and labour and, further, methods of costing, time-keeping and absorption of overhead expenses should be dealt with. The development of initiative should also have special attention, for when men enter into ordinary industrial or business life, very few have to apply solely technical knowledge. The technical knowledge acquired is very often only a means to an end in so far that it enables one to think on the right lines. Men should be encouraged to take part in open discussion on technical and other subjects, to give them confidence in themselves and to develop their personality. Success depends largely on one's executive acumen, initiative and ability to co-operate.

(*b*) *Works committees.*—The author has found the setting up of a works committee to be the most effective way of establishing confidence between the management and the men. It is a most satisfactory channel for bringing before the workers the management's views on all sorts of questions, particularly managerial and labour problems. Further, it enables the management to obtain the workers' views. This gives the workers the feeling that they are being consulted in matters in which they are directly interested, and this in itself removes suspicion. It must be appreciated that economic production can never be obtained unless the men give loyal support to the management. In this connection the author would say that the value of the works committee's support and assistance in the introduction of the system outlined in the paper, contributed largely to the success of the system. This should be ample evidence of the value of a works committee, for if there is one thing that tends to create suspicion and upset the workmen more than any other, it is a change of management and system.

(*c*) *Foremen's meetings.*—In order to stimulate the foremen's maximum interest in the management of their shops and keep them informed on economic and managerial problems, the author has found that monthly foremen's meetings, at which all problems of general interest met with during the previous month are discussed are of great assistance. The foremen have continually referred to the value of these meetings and to the fact that by this method they have received information on matters which, in the past, have not reached them at all.

(*d*) *Unemployment.*—Generally speaking, it may be gathered from conversation with good workers that the greatest brake on efforts of production is the fear of unemployment, and one cannot help but appreciate this fear; for very often a workman with a wife and family to keep can be thrown out of employment at quite short notice with no immediate appreciable visible means of support. A man working under these conditions is naturally tempted to take all possible steps to delay loss of employment and, if he feels that by exerting extra effort he is only completing more quickly the small amount of work that is available, then one cannot get from him his maximum effort. It is not easy to educate and convince a workman that these actions on his part are quite wrong because they cause articles to cost more and therefore make it more difficult to obtain further orders. He can think only of the position as it affects him at the moment, not as it may affect him several months later.

It has occurred to the author that, if we wish to get the maximum effort at all times from the workers, this problem must be dealt with in a more materialistic way than by teaching economics. It is suggested that the creation of a special fund dependent on maximum production during times of good trade—this fund to be applied to carry the workmen over periods of depression—would remove this detrimental effect of fear of unemployment. After all, the creation of such a fund for the workers is nothing more than is generally done in the sound financing of an ordinary business, i.e. the setting up of a reserve fund. Why should not the same principle be applied to the worker? Profit-sharing schemes have been suggested and are very sound, but the worker's argument is: "Why should a high-class workman employed by a firm which is on a sound business footing and earns a good profit, receive more than another man, equally skilled and keen on his work, who is working for a firm which does not earn any profit?" And one can appreciate this argument.

In studying this subject the author has come to the conclusion that this sinking fund could very easily be provided in a "payment by results" works in such a way as to be entirely dependent on the workers' efforts, but should be contributed to by both the employee and the employer.

In the engineering industry agreements already exist by which a pieceworker of average ability must be able to earn $33\frac{1}{3}$ per cent bonus. Most workers by extra effort earn considerably more than this. It would therefore be quite feasible to base this "unemployment sinking fund" on this extra effort, by the employer suggesting that for every 1 per cent earned by the worker over the $33\frac{1}{3}$ up to 50 per cent he will give a fixed sum per 1s. to the fund, provided that the employee will also give a fixed sum per 1s.; and further, for every 1s. over 50 per cent bonus the employer would give a further extra contribution in order to promote extra effort. It will be seen that the employer would thus be giving extra payment for extra effort, such money to be applied to insure the worker in times of plenty against times of depression.

The scheme could be applied to the recognized day workers, such as crane men, shop labourers, etc. The same effort could thus be obtained from all employees of the firm to assist the pieceworker in the production of his maximum bonus. The piecework prices would be set to a recognized scale which could be easily seen. If deemed advisable these unemployment funds could also be used for old age and sickness benefits.

It was pointed out to the author by a workman that many men would be suspicious of the scheme because they would think that employers would know how much money the worker had saved in this way, and would use this knowledge to their own advantage in times of depression, or other times. In order to overcome this, the fund might be administered solely by the various works committees or district committees, and thus the employer would have no knowledge of the sums accumulated for any individual. This fund would be available solely for periods of unemployment due to causes other than industrial disputes, it being clearly recognized that an employer could not reasonably be expected to contribute to funds which might at some future period be used for strike purposes. The details of a scheme of this description must necessarily be bound up in a certain amount of trust between employer and employee, and this can be dealt with through the works committee.

The general handling and education of labour having been discussed, the author proposes to deal now with the way in which technical manufacturing information is conveyed to the workers.

### Technical Process Department.

This department is obviously necessary in view of the fact that many of the problems connected with the manufacture of electrical machinery cannot be left to the shops to solve. The proper solution very often depends on considerable research work and there are often several ways of getting the same ultimate result, but there is only one way which is the most efficient and cheapest. It is the duty of the Process Department to study these various problems and to issue such instructions as are necessary to everybody concerned to assist them in every way. In addition, records must be kept of these various process specifications so that, should there be a change of supervising labour or operating labour, the new man can look up these specifications and so follow on the lines previously worked to. An example of this occurred some years ago, when a man who had been shrinking slip-rings on to mica-covered bushes suddenly left and another man was put on to do the job. The foreman gave what he thought were the correct instructions to carry out the work. About two months afterwards, however, when these slip-rings began to reach the assembly department, it was found that they were loose. On investigation it was discovered that there was no specification and therefore no record of what allowances the man, who had been doing the job for many years, used. In consequence of this a number of experiments had to be carried out and a specification prepared. It must also be remembered that the workman or shop foreman is not always familiar with the details that the designer has in mind. It is therefore of the utmost importance that process specifications should be prepared, particularly drawing attention to the points that the designer wants. In a case which recently came to the author's notice ventilated field coils were provided in a certain machine but no reference was made on the drawing to the fact that the top and bottom washers on the coils should be provided with an opening to allow the air to pass through. In consequence it was not until the machine was assembled and tested that the fact of these ventilating ducts being closed up was discovered.

This department also issues the necessary specifications to enable the buyer to purchase the right sort of materials, many of which have to fulfil highly important functions of which the manufacturer has little knowledge. This section works very closely in conjunction with the research departments.

Appendix 1 gives an example of a manufacturing process, and Appendix 2 shows a purchasing specification for asbestos millboard, showing how the requirements to meet special technical conditions are taken care of.

Having dealt with the handling of labour and the transmission of technical information to the shops, let us now consider the instructions with regard to a mechanical operation.

Table 2.

M.P. & R.F. Dept. Dept. "D." Piecework Time based on one off. Section 1.
Apparatus: . Process Sheet No. 723. Order No.: E.100.
Drawing No.: . Item No. 1. Style: . Date: 3/4/1922.

| Seq. No. | Operation | Finish* | M/C No. | M/C Rate | | Group No. | Labour Rate | | Class of Labour | Process Time | | Process Price | | Awards | | F.E. | | Total | | No. off | Tool No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | s. | d. | | s. | d. | | h. | m. | s. | d. | s. | d. | s. | d. | s. | d. | | |
| 1 | Plane joints and feet .. .. .. | D | M 3 | 3 | 4 | 68 | 45 | 0 | Man | 13 | 0 | 16 | 3 | 3 | 0 | 43 | 4 | 62 | 7 | 1 | |
| 2 | Mark joints for drilling .. .. | | H | 1 | 9 | 11 | 49 | 0 | Man | 1 | 0 | 1 | 6 | 0 | 3 | 1 | 9 | 3 | 6 | 1 | |
| 3 | Drill and S.F. joints .. .. | D | M 31 | 2 | 6 | 24 | 39 | 0 | Man | 4 | 0 | 5 | 2 | 0 | 11 | 10 | 0 | 16 | 1 | 1 | |
| 4 | Joint up .. .. .. .. | | H | 1 | 9 | 11 | 24 | 0 | Youth | 1 | 0 | 0 | 8 | 0 | 2 | 1 | 9 | 2 | 7 | 1 | |
| 5 | Mark setting line for boring .. | D | H | 1 | 9 | 11 | 49 | 0 | Man | 1 | 0 | 1 | 6 | 0 | 3 | 1 | 9 | 3 | 6 | 1 | |
| 6 | Bore and face .. .. .. | | M 6 | 3 | 4 | 62 | 49 | 0 | Man | 10 | 0 | 14 | 0 | 2 | 3 | 33 | 4 | 49 | 7 | 1 | |
| 7 | Mark for drilling complete.. .. | | H | 1 | 9 | 11 | 49 | 0 | Man | 3 | 15 | 4 | 7 | 0 | 9 | 5 | 8 | 11 | 0 | 1 | |
| 8 | Drill and S.F. for poles and feet.<br>Drill and tap for eye-bolts | D | M 22 | 3 | 4 | 63 | 39 | 0 | Man | 8 | 45 | 9 | 10 | 2 | 0 | 29 | 2 | 41 | 0 | 1 | |
| 9 | Drill and tap for rocker .. .. | D | M 31 | 2 | 6 | 24 | 39 | 0 | Man | 2 | 15 | 2 | 7 | 0 | 6 | 5 | 7½ | 8 | 8½ | 1 | |
| 10 | Fettle .. .. .. .. .. | | H | 1 | 9 | 11 | 35 | 0 | Semi-skilled | 15 | 0 | 15 | 0 | 3 | 5 | 26 | 3 | 44 | 8 | 1 | |
| | Total .. .. .. .. .. | | | | | | | | | | | 71 | 1 | 13 | 6 | 158 | 7½ | 243 | 2½ | 1 | |

* A = ground finish. B = lap finish C = water finish. D = dry finish. E = semi-finish. F = rough finish.

### Rate-Fixing and Mechanical Process Department.

In establishing a department of this description, the selection of the personnel is a matter that requires careful attention. In many engineering works it will be found that the piecework times are fixed by the foremen or by rate-fixers who have graduated from the ranks of the workmen without any special training apart from that obtained in the workshops. If the product is of comparatively simple design and construction such an arrangement is generally adequate, but for the complex nature and variety of the parts that go to make up an electrical machine, and owing to the keenly cut prices which have to be quoted to enable home manufacturers to compete with the foreigner, it is essential that not only the piecework time, but the machine and type of tool to be used and the class of finish to be achieved for every operation, be decided by engineers who have the necessary workshop experience and, in addition, who thoroughly understand the functions of the multifarious component parts to be handled.

In order to take advantage of the full capacities of the machine tools and of the improved methods which are frequently introduced by the mechanical process engineers in collaboration with the tool drawing office, it is desirable that the Process Department should consist of two distinct branches. One branch should deal almost entirely with time studies of the feeds and speeds which can be obtained with the improved methods and appliances, and should thereby supply data to the other branch consisting of the process engineers. In this way we can ensure that all piecework times are arrived at on a definite basis with respect to feeds, speeds, etc., and we can consequently eliminate the startling discrepancies which are often found to obtain under those rate-fixing systems where the individual is allowed to express his own opinion.

The Process Department compiles a process sheet for every item for which a drawing is made, and on each process sheet will be found the following information in addition to the operations:—

(1) Process sheet number.
(2) Drawing number.
(3) Item number.
(4) Description of item and style of machine for which it is required.
(5) Minimum number of items to be manufactured at a time to permit of processed time per item being adhered to.
(6) Machine tool to be used if a machining operation.
(7) Hourly rate of the machine tool.
(8) Class of labour to be used on each operation.
(9) Rate of labour to be used on each operation.
(10) War allowances.
(11) Factory expense.
(12) Total cost of labour and factory expense.
(13) Sequence in which the operations are to be performed.
(14) Shops in which the operations are to be performed, and to which consequently the process sheets are to be issued.
(15) Class of finish.

Table 2 shows a typical process sheet for the yoke of a rotary converter.

To ensure that the process sheets are supplied to the departments concerned, the process sheet number and the departments to which the process sheets are to be issued are given against the various items on the manufacturing specifications which are prepared by the drawing office and distributed by the Production Department.

In fixing a piecework time the process engineer bases his calculations on the following assumptions:—

(*a*) That the material will be of average quality of its kind.
(*b*) That the machining allowances will be normal.
(*c*) That the man who is to handle the job will be of average skill, so that he should have no difficulty in making time and a third on the job.
(*d*) That the best machine (if a machining operation) will be available at the time the job goes through.

If the time allotted to the job is disputed by the operator, he refers the matter to his foreman, and if the latter also disagrees with the piecework time, the time-study man for that department is called in to demonstrate what is actually possible. The operator also has the right to scrutinize the detailed figures as calculated by the process engineer which go to make up the total time allowed for the operation (this information, by the way, is filed away in the Process Department with every process sheet) so that he can, if he wishes, point out in what respect he considers the piecework time to be at fault. If it is found that the time allowed is incorrect through some extraneous circumstance, such as unusually hard material involving lower feeds and speeds, defective material, or excessive material allowances on machined surfaces, or owing to the best machine for the operation not being available, then an additional piecework time fixed by the time-study man is allowed for the job, covering the excess time involved only. Under such circumstances the processed time would not be altered.

Whatever the cause, the matter is brought to the notice of the Process Department and, in the case of faulty material, is taken up by them with the suppliers of the material with a view to obtaining a rebate for the extra cost involved in machining this material or, at any rate, ensuring that further supplies will tend to be free from such faults. If, however, the time student's investigation proves the processed time to be incorrect without any such extenuating circumstances, the process sheet is immediately altered by the process engineer and the data from which the processed time has been derived is corrected accordingly. In dealing with disputes, absolute frankness is necessary, and if there is any doubt about the accuracy of the processed figure, particularly of that factor which cannot easily be calculated and is more a matter of experience, namely, the setting up and handling times, then the matter should be carefully investigated and the operators given the benefit of any doubt, unless it is ultimately settled incontestably by demonstration that the processed figure is correct.

Immediately a new drawing is completed by the drawing office, a copy is sent to the Process Department and the process sheets are issued as quickly as possible so that the piecework time is fixed well in advance of the operation being performed. This is very important, as nothing annoys the operators more than not knowing the price they are to be allowed for a job until after it has been commenced or completed, and under such circumstances an atmosphere of suspicion is engendered between workmen and management that is very difficult to combat.

In addition to establishing all piecework times on a systematic basis, the further advantages accruing from the system are as follows:—

(1) The Process Department is in a position to keep the Purchasing Department posted as to the relative merits of materials supplied by different manufacturers. For instance, in connection with steel castings it was found that one firm quoted a substantially lower price per ton for castings than a competitive firm. Orders were placed with both firms and it was ultimately proved that the castings from the latter firm were much cheaper in the long run, as the material was better to machine, the castings were sounder and more accurately moulded and the percentage of rejected castings was much lower.

(2) The Process Department can readily supply the Estimating Department with accurate data for the preparation of estimates, and also advise when reductions can be made owing to the introduction of improved methods or machinery.

(3) Owing to the piecework time being based on the best machine tool being available, certain machines are called upon to such an extent that some of the work necessarily has to be performed on less efficient machines. Records are kept of the extra cost of the work on these machines, and the losses thus incurred will show whether the inefficient machines are worth retaining in service.

(4) A copy of all process sheets is sent to the works costing section so that actual costs can be compared with processed costs as the parts are manufactured.

(5) Disputes regarding piecework times as processed have frequently brought to light the fact that the methods of production as carried out before the introduction of the system were entirely wrong and entailed considerable unnecessary expense, also in numerous cases super-accuracy of finish was being put into parts that were unimportant.

(6) The process sheets enable the Production Department to deduce exactly the time required to manufacture any piece of apparatus. Table 3 shows information taken from the process sheet and assembled to show how the total machine-hours and man-hours on each particular class of machine would be ascertained.

(7) The process engineers frequently find when processing a part that reductions can be made in the cost of production by an alteration in the design which will not interfere in any way with the functions of that particular part.

The production machine basis sheet is prepared from the process sheets. This will be dealt with under the heading of "Production Department."

The author believes that the system has been dealt with in sufficient detail to illustrate the broad principle on which the Rate-Fixing Department should be organized.

The handling of labour, and the transmission of technical and mechanical operation information to the

TABLE 3.

Machine: Type X.

*Part of Progress and Production Chart, in Machine-Days and Man-Days.*

| Part | No. Off | Material | Plane | Mill | M.O. | Drill | Slot | Turn | Fit | Ass. | Fettle | P'ch'gs | Build | Make Coils | Imp. & Wind | Bal'ce. | Erect | Fin. | Paint | Test | Saw | Detail | Total Man-days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Yoke .. .. .. .. | 1·0 | Cast steel | 1·5 | — | 0·5 | 2·5 | — | 1·25 | — | — | 0·75 | — | — | — | — | — | — | — | 2·0 | — | — | — | 8·5 |
| Poles (laminated) .. .. .. | 6 | Core steel | — | — | 0·1 | 0·25 | — | — | — | — | — | 1·5 | 1·0 | — | — | — | — | — | — | — | — | 0·25 | 3·1 |
| Rivets, washers and liners .. | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 2·0 | 2·0 |
| Dampers .. .. .. .. | — | Copper | — | — | 0·1 | 1·5 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 0·5 | 4·0 | 6·1 |
| Interpoles. .. .. .. .. | 6 | Steel plate | — | 0·5 | — | 0·5 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 0·5 | — | 1·5 |
| Studs and screws .. .. .. | — | — | — | — | — | — | — | 1·25 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 1·25 |
| Shunt coils .. .. .. | 6 | Copper | — | — | — | — | — | — | — | — | — | — | — | 5·5 | — | — | — | — | — | — | — | — | 5·5 |
| Series coils.. .. .. .. | 6 | Copper | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Interpole coils .. .. .. | 6 | Copper | — | — | — | — | — | — | — | — | — | — | — | 7·5 | — | — | — | — | — | — | — | — | 7·5 |
| Connections .. .. .. | — | Copper | — | — | — | — | — | — | — | — | — | — | — | 4·5 | — | — | — | — | — | — | — | — | 4·5 |
| Field assembly .. .. .. | — | — | — | — | — | — | — | — | — | 2·75 | — | — | — | — | — | — | — | — | 0·5 | — | — | — | 3·25 |
| Total machine-days for each class of machine .. | | | 1·5 | 0·5 | 0·7 | 4·75 | — | 2·5 | — | 2·75 | 0·75 | 1·5 | 1·0 | 17·5 | — | — | — | — | 2·5 | — | 1·0 | 6·25 | 43·2 |

TABLE 4.

*Part of Main Production Chart.—Output Programme for September.*

| Customer | Machine | Frame size | Estimated weight in tons | Delivery promise to customers | Sheffield delivery promise | Principal specification sheets required | Principal material to be in | Operations | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Machining | Core building | Winding | Assembling | Test, paint and pack | |
| A | Type M.2 motor .. .. | *a* | 4·55 | 30/7/21 | 30/7/21 | 11/3/21 | 8/5/21 | 13/6/21 | 17/6/21 | 4/7/21 | 9/7/21 | 30/7/21 | Delay due: late receipt of material. Machines overdue. |
| A | Type M.2 motor .. .. | *a* | 4·55 | 30/7/21 | 30/7/21 | 11/3/21 | 8/5/21 | 13/6/21 | 17/6/21 | 4/7/21 | 9/7/21 | 30/7/21 | |
| A | Type M.2 Motor .. .. | *a* | 4·55 | 30/7/21 | 30/7/21 | 11/3/21 | 8/5/21 | 13/6/21 | 17/6/21 | 4/7/21 | 9/7/21 | 30/7/21 | |
| B | Type G.2 generator .. .. | *b* | 8·3 | 31/7/21 | 31/7/21 | 28/3/21 | 25/4/21 | 3/6/21 | 8/6/21 | 1/7/21 | 7/7/21 | 30/7/21 | Delay due: difficulty in works. Machine overdue. |
| C | Type G.3 generator .. .. | *c* | 7·1 | 8/8/21 | 6/8/21 | 15/2/21 | 12/4/21 | 24/5/21 | 28/5/21 | 21/6/21 | 27/6/21 | 20/7/21 | |
| D | Type R.2/3 rotary .. .. | *d* | 7·6 | 31/8/21 | 31/8/21 | 9/5/21 | 1/6/21 | 8/7/21 | 13/7/21 | 30/7/21 | 6/8/21 | 27/8/21 | |
| E | Type R.9/11 rotary .. .. | *e* | 11·0 | 6/9/21 | 6/9/21 | 4/3/21 | 31/4/21 | 22/5/21 | 27/5/21 | 22/6/21 | 30/6/21 | 22/7/21 | |
| F | Type R.7 rotary .. .. | *f* | 7·5 | 10/9/21 | 10/9/21 | 19/3/21 | 7/5/21 | 25/6/21 | 29/6/21 | 25/7/21 | 29/7/21 | 20/8/21 | |
| G | Type T.A.15 turbo-alternator | *g* | 10·4 | 10/9/21 | 10/9/21 | 29/2/21 | 24/4/21 | 13/6/21 | 29/6/21 | 3/8/21 | 10/8/21 | 30/8/21 | |
| H | Type R.10/11 rotary .. .. | *h* | 28·0 | 11/9/21 | 11/9/21 | 27/5/21 | 24/6/21 | 22/7/21 | 28/7/21 | 25/8/21 | 1/9/21 | 8/9/21 | |
| H | Type R.10/11 rotary .. .. | *h* | | 11/9/21 | 11/9/21 | 27/5/21 | 24/6/21 | 22/7/21 | 28/7/21 | 25/8/21 | 1/9/21 | 8/9/21 | |
| H | Type A.C. starting motor .. | *j* | | 11/9/21 | 11/9/21 | 29/5/21 | 10/6/21 | 22/7/21 | 26/6/21 | 16/8/21 | 20/8/21 | 8/9/21 | |

men have been dealt with. The obtaining of material and its passage through the shops will now be discussed.

### Production Department.

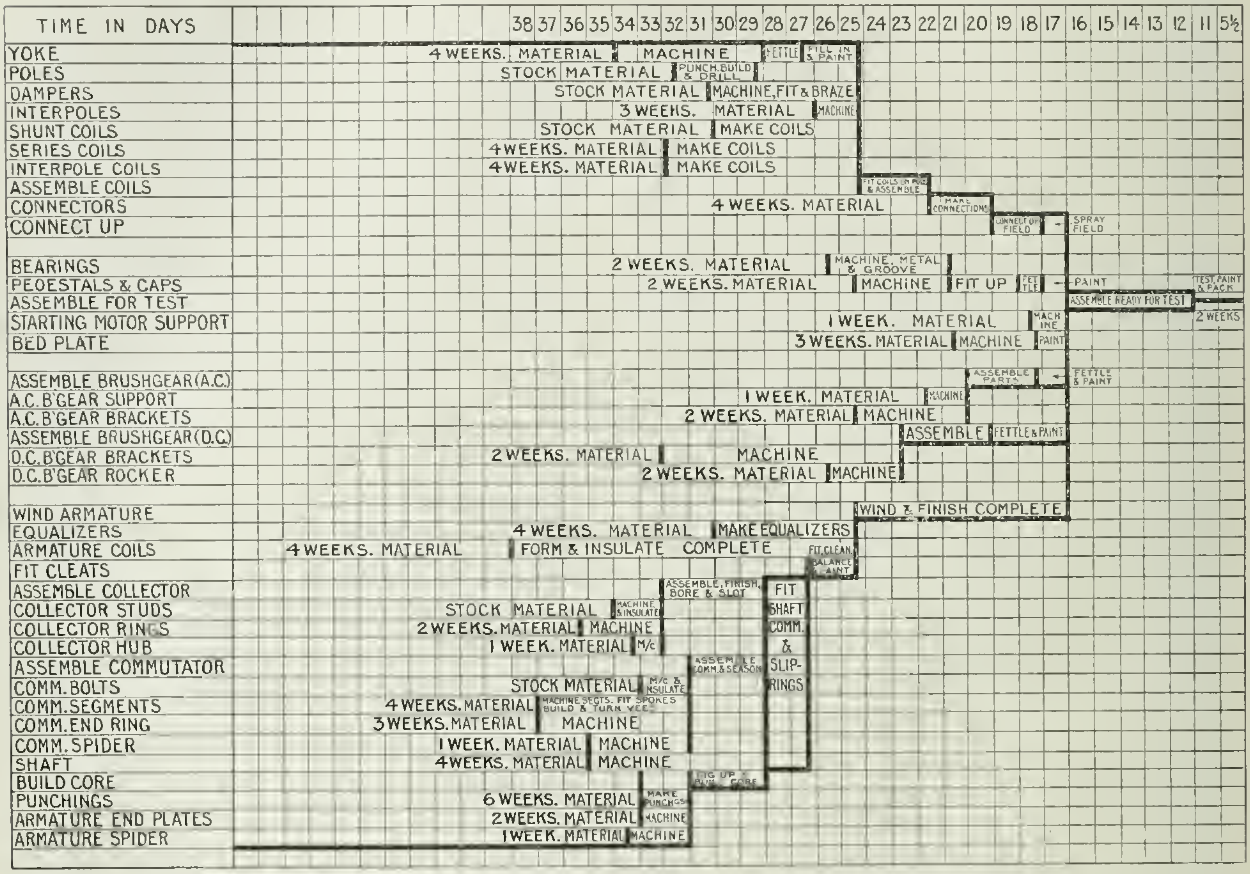
In describing the organization of this section the author would add a few words of warning in choosing the man to run this department. Beware of the high qualification claimed by applicants for the position—such as efficiency engineer and production expert—who are frequently experts in theory and not in practice.

The works manager, who it is assumed is a man of education and very wide practical experience, should direct and control the operation of the Production Department through the chief of that department, in order to ensure that it is not systematized beyond practical and commercial limits. This is very important, as a number of companies have undoubtedly experienced serious financial difficulties through the operation of production theorists.

The capacity of the shop is fixed by the works management in conjunction with the requirements laid down by the sales organization and the capacity fixed by the Production Department. The main shop programme is then prepared. Table 4 gives an example of a portion of a monthly sheet, part of a main production chart, for a shop the normal month's capacity of which was considered to be 300 tons. Each month is laid out similarly and the Commercial Department is advised by the Production Department of forward requirements in good time to keep the shop fully employed. If the orders received monthly exceed the shop capacity, the fact is revealed in good time to enable steps to be taken to deal with it by extending the works, obtaining outside help or increasing the working hours or delivery periods. A list, revised monthly, is sent to the Commercial Department showing the delivery times to be quoted in tenders for all types of machines.

Table 5.

*Machine Production Chart.—Summary for Type X Machine.*



When an order is received it is placed in its proper position in the main programme, which is based on the chart shown in Table 5. The dates are then fixed when the manufacturing information and materials must be available to enable the promise to customers to be kept. These detail requirements are recorded systematically so that they are automatically urged. This urging is divided into three sections:—

(1) Manufacturing information, including specifications and drawings.
(2) Material.
(3) Work in different departments of the shop.

The urging is run on a daily basis so that everything is urged at the right time. This can be easily arranged by having a card for each manufacturing day under each sub-section and entering on it all requirements due on that day to fulfil the manufacturing programme. A fixed period before the requirements are due (if they have not been received) they are specially urged.

For the sake of convenience the Production Department is organized in two sections, one section handling specification sheets, the main production programme, obtaining materials from outside suppliers through the Purchasing Department, and all work inside the office, and the other dealing with materials after receipt in the shops, and the production generally in the shop. The closest co-operation is essential between these two sections.

Table 6.

*Large Machine Department.*

Week commencing March 7, 1921. The following machining to be finished by the dates specified.

*Name:* Mr. X.

| Job No. | Date | Customer | Description | Remarks |
|---|---|---|---|---|
| 275/3681 | 8/3/21 | A | 625/815 kW rotary | Material received 18/2/21 |
| 3685 | 9/3/21 | B | 500-h.p. induction motor | Material received 19/2/21 |
| E.139 | 12/3/21 | C | 380-h.p. motor | Material received 16/2/21 |
| E.152 | 10/3/21 | D | 110-h.p. induction motor | Material promised 24/2/21 |
| E.163 | 8/3/21 | E | 100-h.p. induction motor | Material received 10/2/21 |

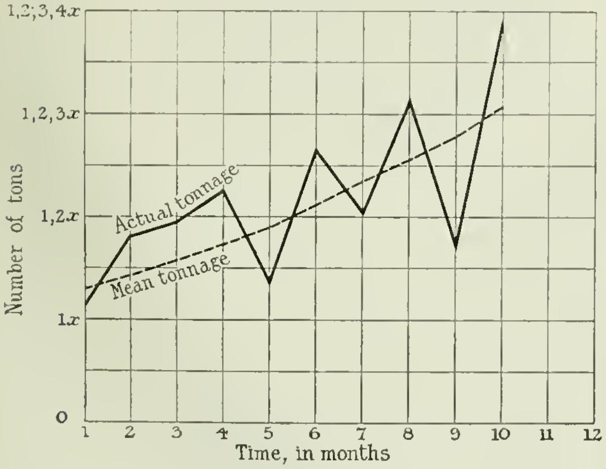


Fig. 2.—Tonnage output.

All manufacturing information from the drawing office is passed through the Production Department and all drawings are subsequently passed through the tool drawing office so that all jig and tool designs are prepared to the date fixed for completion to ensure tools being available by the time material is received.

From the main production chart, records (again on a date principle) are prepared for the foremen of each department in the shop.

Table 6 gives an example of a foreman's weekly production list, as supplied to him by the Production Department. Only one week's work is reproduced in this table but, in practice, instructions for four weeks are given. The shop clerk, who will be at the foreman's desk, will handle these and will be under the general control of the chief production engineer as far as the production matters are concerned. It is the duty of these shop clerks to keep the foremen advised where the material is after receipt from suppliers and to get out the necessary drawings and tools to enable the work to be proceeded with at the right time.

Production meetings are held weekly at which the shop superintendent, buyer, production chief and foreman are present, when details of progress, etc., are discussed.

The curves in Fig. 2 show the effect of a production department's work from its inception until reaching the legislated tonnage output.

The Production Department is responsible for fixing the maximum and minimum stock quantities for all materials stocked in stores.

A return is made to the works manager each week from each department of the items which have not been completed according to schedule, and the reasons for such non-completion.

For a certain works of 700 hands the production staff consisted of:—

1 chief;
2 assistants;
3 clerks; and
1 typist,

exclusive of foremen's clerks, of whom there were 4.

Having dealt with labour and the necessary instructions to labour for technical and mechanical operations to be used in conjunction with the material provided, let us now consider the question of inspection of this material in its initial stages and during its progress through the shops.

## Inspection Department.

In order to ensure that a piece of electrical apparatus when it reaches the test bed has the very best chance of turning out satisfactorily, both to the customer and to the reputation of the manufacturer, it has been found of the greatest advantage to arrange for the inspection and testing of details as the manufacture proceeds through the works. This is of great importance, because if a machine can be shipped immediately after test, and if expensive repairs can be avoided, a manufacturer is better able to fulfil the obligation of delivery.

In the first place, arrangements must be made to inspect and test the raw materials, for, as mentioned above, with electrical machinery the range of materials is so wide that it provides many channels of possible failure. The standard for these materials is taken from the purchasing specification prepared by the Process Department.

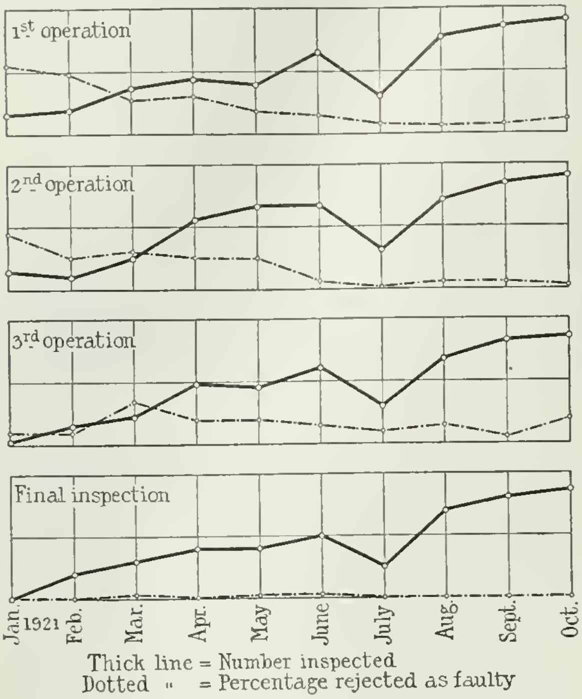


FIG. 3.—Inspection of gear wheels and pinions.

The author has found it necessary that the Inspection Department should take entire responsibility for the testing and inspection of raw materials, but in the shops he prefers that representatives of the Inspection Department should be looked upon in a similar light to customers' inspecting engineers. In other words, they are a safeguard to the management and the foremen, but it is very important to leave to the foremen the real responsibility for the quality of the product. It is necessary that the foremen should feel that the Inspection Department is established to assist them in avoiding mistakes. On no account should the impression be gained that they are spies on the manufacturing section. It is therefore essential that the inspectors should co-operate with the manufacturing section to improve the product and avoid mistakes, rather than criticize. This latter course should be taken only where gross negligence or wilful opposition occurs. The number of inspectors depends on the class of work that has to be dealt with, and as a rough guide the author has found the following proportions to be satisfactory:—

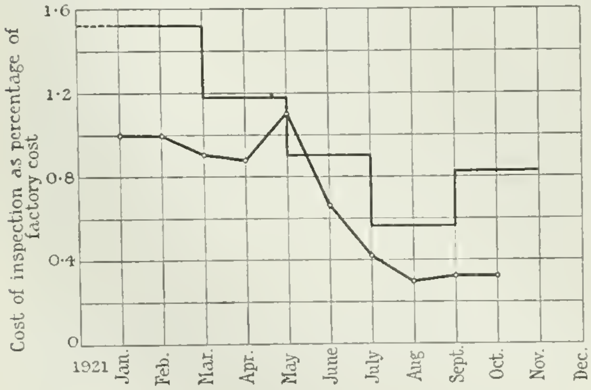


FIG. 4.

Large machine section requires 1 inspector to 60 hands.
Small machine section requires 1 inspector to 70 hands.
Large assembly section requires 1 inspector to 45 hands.
Small assembly section requires 1 inspector to 35 hands.
Large winding section requires 1 inspector to 40 hands.
Coil and insulation section requires 1 inspector to 40 hands.

(NOTE.—Cost of the above is approximately 0·7 per cent of factory cost of output.)

Figs. 3 and 4 give some indication of the results obtained by the introduction of an inspection system. The former shows the small number of defects that appear in the final completed article, and the latter the fall in the number of defects in the final testing department after the introduction of a detailed inspection system. A curve of comparative costs is also shown.

### COSTING DEPARTMENT.

To manufacture a varied product satisfactorily it is necessary to have proper records to guide all parties as to the cost of the product in direct labour and materials and also overhead expenses. During the introduction of a costing system, the first essential to impress on the members both of the manufacturing and of the costing staff is that the closest co-operation must exist between them. The Costing Department is not a spy on the Manufacturing Department, but a useful and constructive portion of the manufacturing organization. Its duty is to assist the manufacturing section by giving such figures and help as to enable them to ensure that excess costs do not occur. It must be realized that the foreman in the shop cannot possibly carry the cost of all different operations and factory expenses in his head, and he must be encouraged to co-operate with the Cost Department and to have confidence that they will assist him.

Costing can be conveniently divided into two sections:—

(1) Consisting of direct labour and materials.
(2) Consisting of factory overhead expenses.

(1) *Costing direct labour and materials.*—The author has experienced great difficulty in cases where costs are not available until a machine is finally completed. By this arrangement, if a machine takes several months to manufacture it is impossible to investigate operation costs because they are received a considerable time after the operation has been carried out. This emphasizes the necessity of a costing system being elastic as well as prompt.

An elastic system has many advantages, and one with which the author is now acquainted has been found to contain the very elements necessary to avoid losses which might recur in possibly the course of two months in a works where repetition work is engaged in to some extent. It also provides the means of producing efficiently and cheaply, by reason of the fact that particulars can be obtained of the time taken, the number of operations employed, the size and rate of machines used, and the cost of labour.

For many reasons it is of the utmost importance that a sound costing system be installed. In this connection, in the particular works with which the author is associated, the features that have had most consideration and which are of paramount importance are: To provide operation costs as quickly as possible after an operation has been carried out, so that the actual cost can be compared with the planned process. After all operations on a piece of apparatus have been thoroughly standardized and the comparison between cost and estimate shown, and the planned piecework prices fixed, then, provided a proper check is kept on daywork, there is not the same need for keeping a comparison of operation costs, and the final cost of the completed machine is the only check that is essential. In the starting up of manufacture of a piece of apparatus of new design, however, operation costs, prepared immediately after the work is carried out, are essential.

In order to make this scheme operative, a complete detailed list of the planned operations should be forwarded by the Mechanical Process Department to the Cost Department, each operation to be given a number for the purpose of comparison.

In many works what is known as the "Hollerith" card index system has been introduced for the recording of costs. This is certainly very sound, but in its introduction very careful consideration must be given to the question of flexibility, for unless the system is properly laid out the Hollerith system can be far from flexible. The most important point about a costing system is that it must not give either too little or too much. If the former, it becomes useless because the information is incomplete, and if the latter, more money is being spent than the value obtained from it. It is obvious, however, that it is better to have too much than too little.

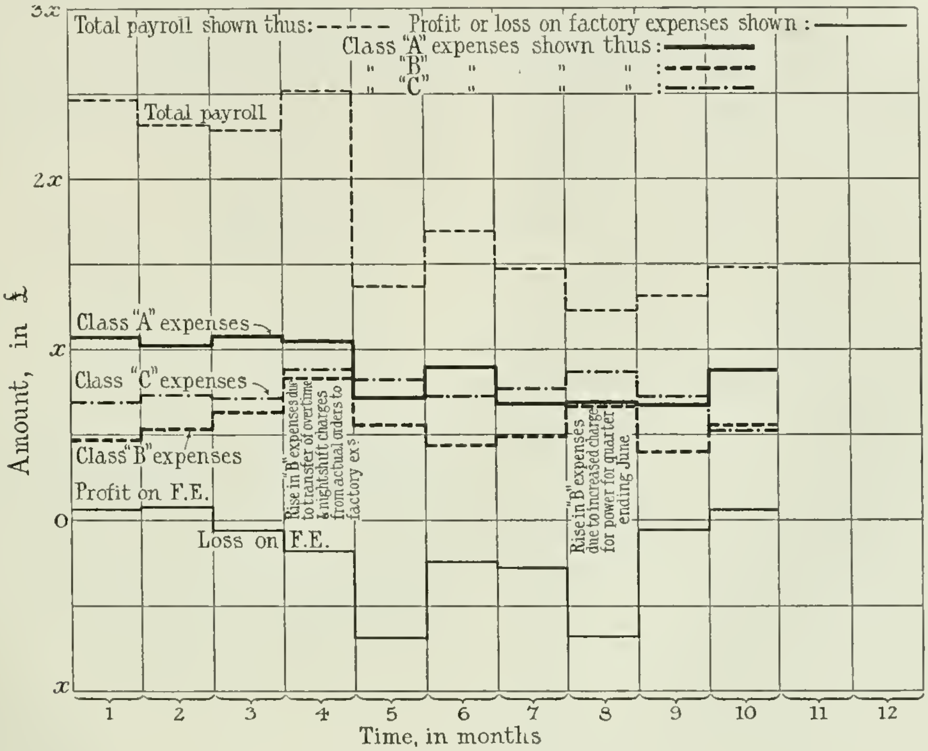


FIG. 5.—Relationship of pay-roll to expenses.

(2) *Costing factory overhead expenses.*—The overhead charges must be properly provided for and, in the author's opinion, a machine rate basis is the only sound way to effect this. A percentage on labour is quite wrong and to emphasize this one has only to take the case of a man and a boy working on the same machine. The man's rate may be 1s. 6d. per hour, and by the percentage basis the overhead charge on his labour, if the ratio is 100 per cent, would be 1s. 6d. For a boy on the same tool at 6d. an hour the charge would be 6d., and, if one considers in detail all the expenses that go into overhead charges, it will be found that the charges per hour for a lower rate of labour are quite as much as for the higher, and very often more, as boys damage more tools and require more supervision per unit of output. With the majority of the

machine tools at the author's works the machine rate basis is taken as 40 hours per week, the difference between 40 and 47 being the average loss of time in the running of the machine due to various causes, such as breakdowns, men absent, getting together tools, etc. The machine rate basis is arrived at by allocating a portion of the fixed charges (such as rates, rents, taxes, depreciation, etc.) for the floor space occupied by the machine and the surrounding space necessary for storing the raw and finished product.

Power charges are obtained by taking the actual power measurement of the machine. Tool charges are arrived at by estimating the value of tools used in a definite period and employing this as the basis for an average hourly cost for tools. Hourly charges per machine are arrived at for depreciation, general shop labour and materials, operation of cranes, etc.

The author has heard the opinion expressed that it would be difficult to apply this system to an old works. However, at the works with which he is associated in Sheffield, employing up to 1 000 hands, this system was instituted and was running satisfactorily in 3 months.

Having arrived at this basis of machine charge, it is important to see that the factory expenses are collected and recorded in such a way that they can be easily watched to make sure that there is no mistake in the estimating of overhead charges, and that proper figures have been fixed for absorption. The assembly of these expenses should be such that they can be easily understood and watched by the heads of the various departments. In the works referred to above, these expenses are recorded in the following three groups, each item being given a number, to which all expenses on that item are charged :—

(A) Items controlled by the foremen. Full particulars of these are sent to each foreman monthly, so that he can take an intelligent interest in the money he is actually spending and keep down unnecessary expenditure.

(B) Items controlled direct by the Superintendent of the works.

(C) Expenditure controlled by the Board and General Management.

Lantern slides will be exhibited showing details of these groups.

This type of division may not be necessary in a smaller works, but the basis should be the same, for this paper was written to draw attention to a basis of an organization, as before mentioned, rather than to give details of a particular scheme which may not be applicable to more than one works.

By this method of recording factory expenses a more direct interest in the efficiency of the department is created, because the foreman realizes that he has something which he is able to control.

Fig. 5 shows the variation of labour and factory expenses and their relation to the absorption of factory expenses. In many works it is the practice not to give foremen details of this description. The author considers that a foreman should be looked upon as the manager of his own department and should be given such information as will enable him to manage. The owner of a factory would not attempt to manage it unless he had the necessary figures put before him.

Finally, a monthly summary of expenses is prepared, as shown on the lantern slide.

### Relation between Output and Costs of Production.

The question of factory expenses has already been referred to. The author will now endeavour to show the distribution of these expenses. For the sake of simplicity let us consider a factory that is making one class of machine of one size. The factory cost of this machine consists of the cost of material, the cost of labour and its share of the factory expenses, and this share of the factory expenses is proportional to the output. In other words, the total factory expenses divided by the number of machines shipped per year equals the factory expenses chargeable to each machine. For example, let us assume that the normal output of a certain workshop under a moderate management is 1 000 machines a year. The basis on which the selling price is arrived at is obtained as follows :—

| | £ |
|---|---|
| Cost of material .. .. .. .. | 20 000 |
| Cost of labour .. .. .. .. | 6 000 |
| Factory expenses .. .. .. | 6 000 |
| Estimated selling expenses .. .. | 8 000 |
| Total cost of 1 000 machines .. | 40 000 |
| Total selling price (including 10 per cent profit) .. .. .. .. | 44 000 |
| Selling price per machine (including 10 per cent profit) .. .. .. | £44 |

Now let us consider this same shop working under bad management and producing only 500 machines per year, and the same shop under a very efficient management, working day and night, producing 2 000 machines per year. The table below illustrates very clearly the effect of this on the possible selling price. It will be noted that we get the enormous difference in price of 50 per cent for the same article.

*Output per Year.*

| | Under bad management. 500 machines | Under excellent management. 2 000 machines, working day and night |
|---|---|---|
| | £ | £ |
| Cost of material .. .. | 10 000 | 40 000 |
| Cost of labour .. .. | 3 000 | 12 000 |
| Extra for night work .. | — | 3 000 |
| Factory expenses .. .. | 6 000 | 6 000 |
| Extra for night work .. | — | 1 500 |
| Selling expenses .. .. | 8 000 | 9 000 |
| Total cost of machines .. | 27 000 | 71 500 |
| Total selling price (including 10 per cent profit) | 29 700 | 78 650 |
| Selling price per machine (including 10 per cent profit) | £59·4 | £39·325 |

These two figures compare with £44 for the factory manufacturing 1 000 machines a year. They are comparative for a high-class electrical engineering shop, where the overhead charges are relatively high due to the necessity of employing a large staff in the engineering and draughting offices and in the selling section.

This subject can also be studied from another point of view, namely, that of profit. If we assume that the motors have been sold under all conditions at the fixed price of £44, the effect of decreased output is shown clearly in the following table:—

*Output per Year.*

| | 1 000 machines | 500 machines | 2 000 machines (working day and night) |
|---|---|---|---|
| | £ | £ | £ |
| Cost of material . . . . | 20 000 | 10 000 | 40 000 |
| Cost of labour . . . . | 6 000 | 3 000 | 12 000 |
| Extra for night work . . | — | — | 3 000 |
| Factory expenses . . | 6 000 | 6 000 | 6 000 |
| Extra for night work . . | — | — | 1 500 |
| Selling expenses . . . . | 8 000 | 8 000 | 9 000 |
| Total cost of machines . . | 40 000 | 27 000 | 71 500 |
| Total sum received (at £44 each) | 44 000 | 22 000 | 88 000 |
| Loss on working . . . . | — | 5 000 | — |
| Profit . . . . . . | 4 000 | — | 16 500 |

From this it will be seen that a loss of £5 000 is turned into a profit of £16 500, merely by increasing the output. This clearly shows the importance of the selling staff obtaining orders, and the works staff doing everything possible to enable a greater output to be obtained than that estimated for.

In conclusion, the author would like to urge that the principles outlined in this paper can be applied very profitably outside the ordinary manufacturing problems. For instance, the power station engineer increasing his plant can lay out his extension programme to ensure that his orders are placed at the right time, i.e. neither too early nor too late, and thus avoid:—

(1) Capital lying idle and plant being delivered before it is required.
(2) Delays in completion (involving capital lying idle on account of plant that is delivered in time waiting for plant that is late).

Further, this will avoid plant being stored in the works after the foremen and men have been urged to complete it. This, it will be appreciated, has a very bad moral effect on all those concerned.

It will be of interest to know that the author has recently returned from a tour of inspection of conditions in American works, where he did not find any organization which could improve that outlined in this paper for handling a varied product. Further, he found that the average manual employee in the United States gives a greater output than is generally found here. In the author's opinion this is accounted for by the confidence established there between employer and employed. The necessity for the establishment of such confidence in this country and the suitable methods for realizing it are emphasized throughout the paper.

We, as electrical engineers, can certainly take great pride in the fact that our efforts have already been of very considerable benefit to the community, particularly to the working classes, as, for instance, they are now able to go to their work by tram at very cheap rates and in a very short time, whereas previously they often had to walk miles. I think all of us realize that our work has only begun and that by proper organization in the manufacture of electrical apparatus of every description we should lead to the more extended use of electricity for heating and power.

A number of lantern slides will be exhibited showing a shop laid out with galleries supplying main centre aisles, and a shop laid out to give continuous advancing operations on one floor.

In conclusion, the author must express his thanks to Messrs. The Metropolitan-Vickers Electrical Co. for giving permission to publish so much information on the running of their Sheffield works. He is also indebted to Mr. H. F. Brown and Mr. McMurray for assistance in editing proofs during his absence in America.

## APPENDIX 1.

### *Process Specification for Moulding Mica to End Rings for Large Rotors.*

*Material.*—Mica splittings, Grade 4 (area 2 to 4 square inches), shellac varnish (specific gravity 0·930).

*Process.*—The moulding mica shall be cut in sections and the part of the mica which is to fit over the tapered end of the ring shall have fingers cut to the depth of the spigot.

The ring shall be thoroughly cleaned with a cloth which has been dipped in methylated spirits, and then wiped dry. A coat of shellac varnish (specific gravity 0·930) is then applied to the ring where the first section is to be placed. The moulding mica is then placed on a hot-plate and one side is given a coat of shellac varnish (specific gravity 0·930). As soon as the section is soft enough for moulding it is placed in position on the ring and rubbed down with a dry cloth. The end with the fingers cut in is to be ironed down with an iron. All the following segments are then treated in exactly the same manner, but when placed in the ring the butt joint is made leaving about 1/16-inch clearance between the segments. All the following segments are then placed in the ring in the same manner.

Four layers of 1/32-inch moulding mica (mica is milled 28 to 32 mils) are to be built in the ring in the same manner as the first layer, staggering the joints as each layer is built.

It is essential that the thickness of mica shall be the same in each layer.

*Moulding.*—The mould is heated in a gas flame at a temperature of approximately 210° C., and then placed in the mould and screwed down tight. At the same time a cold mould shall be placed on either side of the hot mould, to prevent getting any creases in the mica where the edge of the hot mould is pressing.

This operation is repeated until the whole of the ring has been moulded, and care should be taken that the mould is not unscrewed until it has cooled down to a temperature between 30–40° C.

When the above operations are completed a large mould made to fit inside the ring is placed in position and screwed down hand-tight by means of clamps. The whole is then placed in an oven, the temperature raised to 150° C., and baked for 15 hours. As soon as the temperature has reached approximately 90° C., the ring is removed and screwed down as far as possible. It is then returned to the oven to complete the baking process.

After removal from the oven the ring is allowed to cool down to a temperature of 30–40° C., before removing the mould.

## APPENDIX 2.

### *Purchasing Specification for Asbestos Millboard.*

*General.*—This specification covers a soft, porous, rough-surfaced asbestos millboard suitable for use in the manufacture of arc shields, etc.

*Dimensions. Thickness.*—The asbestos millboard will be ordered of a nominal thickness of 0·063 inch with tolerances ± 0·01 inch.

*Size of sheets.*—Sheets will be supplied in sizes from 3 to 4 feet square.

*Finish. Stiffness.*—The sheets shall be sufficiently stiff to permit of their being readily handled for the purpose of cutting and sawing to any required shape.

*Surface.*—The material shall present a rough porous surface which will readily permit the penetration of silicate of soda during process of manufacture into arc shields.

*Physical properties. Softening.*—When placed in a hot solution of commercial silicate of soda (specific gravity 1·25 at 20° C.) and maintained at this temperature for 1 hour, the sheets must become soft and pliable and must not become pulpy or fall to pieces when handled.

*Moulding.*—Ten pieces of asbestos millboard 5 inches × 5 inches will be soaked for 1 hour in silicate of soda (specific gravity 1·25 at 20° C.) maintained at 85 to 90° C., after which they will be placed between metal plates and subjected to a pressure of 300 lb. per square inch and to a temperature of 100° C. for 3 hours. This test should produce a hard, solid piece which when struck with a piece of metal produces the ring of a tile or hard brick.

## DISCUSSION BEFORE THE INSTITUTION, 18 JANUARY, 1923.

**Mr. H. Mensforth:** I think that in dealing with workpeople the author adopts rather too patronizing an attitude, and particularly is this the case in connection with the teaching of economics. He mentions the latter on so many occasions that one is almost driven to the conclusion that he thinks that it will act as a sort of anæsthetic on the workman, and that the workman accepts the employer as a proper teacher of economics. I do not think that such is the author's opinion, though that is a possible construction to put on his paper. My experience is that when one talks economics with a workman one finds that he is not so ignorant on the subject as one might suppose. He has his own views, and one would not get very far in teaching him this subject as usually understood by employers. For instance, one of the first questions that a workman would put would be as follows: "Separating the factory cost (which consists of labour, factory overhead, and material) from the selling price, what is the selling price? One will often find that the factory cost which includes the above components is only 50 per cent of the selling price, and if this is so, cannot savings be effected in this direction?" A further point is that in dealing with factory expense labour itself, in some form or other, is one of the largest components, but labour (i.e. productive labour) is not the largest component of the factory cost of a piece of material, and the tendency to-day is to devote too much attention to this element of the cost of the product. I notice in regard to the organization charts which the author gives that he excludes what I should consider to be one of the most important sections. I refer to the estimating section. The author mentions a sinking fund to be derived from a piecework effort of the workmen. Whilst the principle may be sound, and whilst the author's views thereon are undoubtedly so, I think that the method adopted of expressing it is rather unfortunate, because it is stated that the fund is solely dependent upon the workmen's efforts. The author makes a statement about a 33⅓ per cent bonus, and this should, I think, be corrected. The fact is that the agreement between the employer and the employee provides that a man of average ability shall be able to—not must—earn a bonus of 33⅓ per cent upon his basic rate, not upon his wages. As regards piecework price-setting, I think that the author has forgotten one fundamental thing to which attention should be drawn, namely, that the agreement which exists between the employer and the employee is that the price paid shall be an agreed price, and that all piecework prices shall be subject to such agreement and also to mutual negotiations. The author points out what machinery will operate provided the man is dissatisfied, but he does not point out what the machinery or organization is which will operate if the disagreement continues after the stage to which he refers. The function of the table on page 350 is to exhibit the influence of output upon cost. I wish that the problem were as simple as is indicated therein. There are many additional factors to be considered. In the first place, the author gives a factory expense component of £6 000. There is no engineering concern, of which I have any knowledge, working with a factory expense component of £6 000 associated with a labour component of £20 000. Further, I do not know of any concern which can increase its output by 100 per cent, i.e. from 1 000 to 2 000 units per year, without a material increase in its overhead charges. The cost of maintenance of the machinery is very much higher; the cost of power also is very much higher. Extra lighting and heating are necessary, so that the figure might be quite different. I admit at once that some advantage would accrue, but it would not be as great as the paper seems to indicate. As regards works committees, I am in full agreement with the author. I entirely sympathize with the idea of putting before workmen any fact which they can absorb, taking steps which will help them to absorb it and doing anything within reason which will make their job more interesting. The majority of works committees in this country have failed because the employers have not had sufficient courage to give the men scope to be operative. They have been hedged round by constitutions. The only efficient constitution for a works committee, according to my experience, provides that the committee is definitely concerned with anything inside the organization which interferes with its efficient running. The workmen are entitled to bring up anything which, in their opinion, interferes with that efficient running and to have it discussed. Further, they are entitled to bring up any grievance. Whether the grievance be real or fancied, it is equally dangerous and should be removed. If that is observed, then a works committee is efficient. The author spoke of his visit to the United States and of what he saw in the Ford factory. I also have been to America recently on a similar trip, and I found that, without question, more is produced per unit of labour involved, for the reason that the work is better arranged. A man has always got some job ahead of him. In this country generally a man does not see what his next job is going to be, but in the United States the feeding of the work is better, and so also are the means of production. In an engineering organization the works can well be separated into two distinct parts: (1) the production, and (2) the means of production. The ordinary shop staff whose job it is to look after labour and to see that it is properly controlled and guided should not be made responsible for the means of production.

**Mr. G. Hurford:** The author has stated that it is very useful to have one meeting a month with the foremen in order to explain the company's point of view. I would point out that it is just as important that the foremen should be allowed to explain their own difficulties, as my experience has shown that they nearly always have more troubles and difficulties than the management. With regard to the balance sheet which the author has brought forward, he says that the cost of selling 1 000 motors is exactly the same as that of 500 motors, but he only allows another £1 000 when he sells 2 000. My contention is that the cost of selling 500 motors is not the same as that of 1 000. There is naturally a reduction; otherwise it would be reasonable to assume that it must cost the same amount to sell 2 000 as it does to sell 500.

**Mr. W. F. Higgs:** The author refers to the "ca' canny" principle of the worker and shows how this can be eliminated by the management. He also says that the heads of the factories must be students of human nature—pointing out that defects in management originate, to a large extent, in the heads of the firm rather than in the workmen. He also refers to the complex articles manufactured. The only way of overcoming the difficulty is, I believe, by specialization. I do not consider that the electrical industry is specialized to the same extent as kindred industries. The result is that we have got to specialize and confine our energies to a small number of articles. On page 340 the author says: "This was satisfactory in the past when competition was not keen and the margins of profits were much higher." I believe that to be a fallacy, for the reason that in the past men were only competing against men, and to-day we are doing the same. We have additional knowledge certainly, but our competitors also have that. The return on capital over a long period is a sure test of organization. The author has pointed out how his system has considerably reduced the cost of production. I had the unique opportunity of being with two firms manufacturing the same class of article in the same district, employing the same class of labour. For years one firm barely struggled along, whilst the other regularly made 50 per cent profit on its capital, due purely to improved organization. I agree with the author that sufficient attention is not paid to the design of castings. It is surprising how much trouble a man will cause by adding a little projection which in the majority of cases could be eliminated or substituted, a core box being thereby saved. With reference to piecework, there is a leading factory in this country manufacturing switchgear—probably one of the biggest factories in the country—which now adopts day-work and makes as handsome a profit as firms which have adopted piecework. I should like to know if the author is really a firm believer in piecework. He refers on page 344 to the operators working piecework and starting on the job before the price is known. That is not piecework, and herein lies some of the difficulty of organization. Clear drawings undoubtedly constitute the foundation of factory management and works production. I am convinced that sufficient attention is not given in the average electrical factory to this point, particularly in comparison with the petrol-motor industry. With regard to the author's warning as to the Production Department, I consider that the latter can be easily overdone. Much of the trouble in the Production Department can be eliminated if the Design Department refrains from taking $33\frac{1}{3}$ per cent of the time required for delivery. No reference is made in the paper to the importance of detail on lists of material. When the rotary converter to which the author referred is nearly ready for test, it is usually not the spider casting or the shell casting that holds it up, but a trivial matter of two or three rivets. Referring to the different rates of pay of men on machines, I should like to know the author's opinion of the suggestion that the basis of piecework should be time rates instead of money rates.

**Mr. Kenelm Edgcumbe:** I am pleased to see that the author lays stress on the study of economics. I almost look upon this as a more important factor, in many ways, than even committees, and so on, in bringing about good feeling in the works, because however good the feeling on those committees may be, there are bound to be occasions when the management and the men's representatives do not see eye to eye, and it is extraordinarily difficult to put one's case to a man who has had no grounding in the fundamental common-sense of economics. The better class of man, no doubt, has a rough and ready knowledge of the subject, but the average man whom one encounters is lamentably deficient in this respect. This is doubtless due to our modern system of education, rather than to any mental failing. I feel sure that it is time the question of common-sense economics was taken seriously in hand.

**Mr. J. R. Cowie:** Reference is made in the paper to the Production Department and to the Process Department. These, however, deal with materials, and that brings in the Stores Department, which is not referred to under the main headings of the paper. If the stores have fallen behind, the whole operation is delayed. The other point to which I wish to refer comes under the heading of design. Due to that a works can be stopped altogether, because, as I read it, included thereunder is the actual electrical or mechanical design and the actual drawing-office work, and in some instances of very special items the whole of the delivery time can be spent in these two sections. It seems to me that either the Process Department or the Progress Department must have some correlation with design in its truest sense.

**Mr. F. Tremain:** I was very gratified to find the importance attached in the paper to the Inspection Department, which branch, in a well-conducted works, is becoming more and more recognized. In my capacity as inspector for the buying side, during a period of about 12 years, I often found opportunities of suggesting to manufacturers methods of economy, and, to my employers, the introduction of modifications in specifications in future jobs, which would reduce the cost —which, of course, the buyer has to pay. I was also glad to see that the author referred to the so-called "finished product" that comes out of our universities. It is deplorable to find so many graduate engineers unable to get a job. I think it is often because their training in many of the technical colleges is too academic, and it should be pointed out to our professors that their curricula as regards engineering training appear to require some modification.

**Mr. R. S. Allen:** Fig. 1 shows the co-operation between the various sections of the works management, but no reference is made to the Purchasing Department. I consider that to be a very important section of any works, and its absence is indicated in the tables on page 350 showing the costs of various numbers of motors, where the author points out that the material per machine for 2 000 motors is the same as for 500. It seems to me that the Purchasing Department should get a much lower cost for the larger number. On the subject of rate-fixing, the Planning Department fixes the price in the early stages, and the foreman of the department may have both a planing and a milling machine, with either of which an operation may be done. The price being fixed for the less expensive operation, how is the price adjusted for a more expensive? The fact that a youth may be required to do a job which was intended for a man, or vice versa, also requires adjustment. These are difficulties which, I think, militate against the early settlement of prices. It is not by way of criticism that I raise these points, but merely for information, because in many works the price is not fixed before the workman about to do the job asks for it. Can the author state the percentage of office staff to workmen for the Rate-Fixing, Process and Production Departments, as he does for inspectors on page 348? The sinking fund for unemployment is a very admirable conception, but I think that there would be a good deal of difficulty in applying it. Will the individual who is fortunate enough to earn a super-bonus benefit entirely by his work, or will he help to support those who are not so fortunate? On the subject of "ca' canny," the workman is only following the lead set by the employer. If work is not coming in as it should do, and there appears to be only one or two months' work ahead, men are discharged to spread the work over a longer period. This example is followed by the men in order to avoid being discharged. That is the situation for which I can suggest no remedy. Until men understand why it is necessary for the employer to follow the course he does, due to the immense difficulty in re-starting a works once closed, they will, I suppose, continue their present practice. On the subject of inspection, I would ask the author whether the inspectors overlook a man while he is doing his work, say while he is operating on the first few articles, or whether they wait until a batch is completed and therefore possibly have to condemn the lot rather than a few.

**Major H. Brown:** Is the Institution aware that during the past 5 or 6 years there has been a very appreciable falling off in the facilities for technical education that are open to workmen? In 1918 the Board of Education decided to abandon the examinations in science that they previously had held, and shortly after that the City and Guilds of London Institute followed suit as regards technical subjects. With the exception of examinations in Telegraphy and Telephony, Gas Engineering and, I believe, Electric Wiring, which are continued by special request, the City and Guilds Examinations have ceased. That means that the better class of workman is now unable to produce satisfactory evidence of education beyond the standard of the ordinary council school. There is now no widely recognized technical examining authority in this country between the ordinary council schools and the universities. This is a serious discouragement to the more ambitious workman, and I wonder whether the author has done anything in his works to fill that gap.

**Mr. H. W. Richardson:** I cordially agree with what the author has said in regard to education. I also agree to some extent with what Mr. Mensforth has said about some workmen not being quite so blind to economics as might seem to be the case at first glance. Usually, however, there are some eight or ten stock questions which 90 per cent of workmen put, these having been drilled into them by trade union agitators. With reference to Mr. Mensforth's point about 50 per cent of the selling price of goods being absorbed by works costs and the other 50 per cent being regarded by the workmen as profit, I think it is possible to make the majority of workmen realize that such things as distribution costs are essential and that these are bound to account for a proportion of what at first sight seems to them to be profit. In the main there is room for a great deal of improvement in the methods of attempting to give a real grasp of the fundamentals of economics to working men. I do not think that a great deal of educational work is likely to be done by means of lectures. More can be done by individual effort, and it is the duty of those who do get opportunities of speaking to the workmen from time to time to do some real "spade work." We should endeavour to show them what increased production and the lowering of costs really mean; graphical work will be of considerable assistance. In Fig. 1 "Designing" appears to be rather isolated, and I feel that an additional line should be drawn on the diagram connecting it with "Production." In the same way "Designing" might be joined to "Process," so that the former would be linked to other departments as the author really intends it should be. In regard to co-operation, the meetings between the heads of the departments and others must be regular; it is no use having more or less casual meetings. There should also be firm agenda on which the discussions can be based. A previous speaker mentioned the importance of the Buying Department; closely linked with this is the stores. The importance of having these properly laid out, with easy exits and entrances, cannot be over-estimated. In some works the stores are situated behind a pigeon-hole, the men having to form up in a queue and wait, thus involving a great deal of loss. As much space as possible should be devoted to the stores, which should be in very close touch with the Production and Process Departments, particularly the former, so that sufficient notice may be given as to the material required. The transport within a works affects production tremendously. Of late years a certain amount has been done with electric trucks. These are somewhat cumbrous in appearance but very mobile. There is nothing more annoying for a worker than to find, after a particular piece of material for which he has been waiting has been brought on a hand-truck, that he cannot get it on to his machine because the overhead crane is employed elsewhere. In a shop fitted with small auxiliary runways of fairly large radius any delay of that kind is obviated. There is also the question of the arrangement of machines in the workshop, which is very important. The grouping together of too many machines of one class does not tend to efficiency. I think that the best method is to arrange together a few machines of each class necessary for performing the complete series of operations required upon the parts to be dealt with. Then, with the aid of two or three of the auxiliary runways referred to above, a given part can be machined from start to finish with a minimum of handling.

**Mr. W. E. Burnand**: I can hardly agree with the author's remark on page 340, that "the time is past when a technical business can be run by one man." If he had said that possibly the days of such businesses are numbered, I might be more inclined to agree, but I should not predict the number of days still left for them. In every case, success in running either a big business or a small business depends upon a realization and an efficient utilization of the possibilities of the particular business, and even more so upon a realization of its limitations. To attempt to run a small business on the lines of a large one very quickly results in disaster; and, similarly, to attempt to run a large business on the lines of a small one results in chaos. It would not be possible for me to make machines in a small shop to-day and sell them at a profit, as I am doing, if the larger works were efficiently run and organized. The fact is that even these larger works are in only an incomplete state of development, with many of the handicaps of the small concern as well as the high costs of a large concern, without sufficient output to carry these costs unless they are excessive per machine. Until more efficient standardization is adopted and a large-scale grouping of manufacturing interests effected, making real quantity production possible, electrical manufacturing can only make slow progress through its present awkward stage. In this connection Table 2 is striking, as showing piecework time based on one article in a large works, and Table 5 gives a good idea of the amount of time taken to obtain material which, however, should be a steady flow not identified with any particular order on really large-scale production. I believe Table 5 to be on sound lines with the present quantities, and that, as stated by a former speaker, Americans owe much of their success to the fact that they plan ahead farther than we do. I entirely agree with the author as to the value of detailed production and process records. Whilst feeling inclined to criticize a number of figures in the tables on pages 350 and 351, taking them as a whole I do not think that they are really such a long way out as might appear on a casual inspection of isolated items. One has to judge a system by the results, and the fact that the author is decreasing the work in progress from 7 to 4½ months is, I think, sufficient proof that the system is a good one. Table 2 affords another illustration of the value of a good load factor. On one of the slides shown during the meeting I noticed that the speed of drills was expressed in revs. per minute. I would suggest the following as an improvement. On each drilling machine I have a card with speeds not specified in revs. per minute, but in certain notches—1, 2, 3 or 4—as correct for holes of various sizes in different materials. Thus, if a man is drilling a ¾ in. hole he should use, say, notch 3, but this is not compulsory. I simply say: "That is the right speed for average material," and a man can use that speed or not, but if he is on another speed I want to know the reason, and very often there is a sound reason, such as hard material, or extra depth of hole, both of which have a very great influence on the speed and feed for efficient drilling.

**Mr. P. M. Baker** (*communicated*): The subject of the paper—production on a sound economic basis—is one of the greatest importance; it is in fact vital to our economic life. It is, at the same time, a side of their work to which engineers and managers rarely seem to attach sufficient importance. As emphasizing this point I will call the attention of members to the recent articles by Lord Weir (*Times*, 13 January) and Lord Milner (*Observer*, 14 January, *et seq.*) and to the speeches of the Rt. Hon. R. McKenna at the annual general meeting of the London, City and Midland Bank, perusal of which will help us to clarify our ideas on the subject. The author bases his paper, as I read it, on a premise that we can only retrieve our position in the manufacturing world by adopting every possible means for securing cheap and efficient production—a proposition which is so abundantly proved that one marvels at the view escaping any thinking man. It is far from being generally appreciated that economic laws are just as inexorable as physical laws and that legislative tinkering in economic matters, such as the fixing of rates, early closing of shops, etc., can only restrict trade; they cannot alter its economic basis. I am generally in agreement with the author's statements, but there are two points to which I should like to refer. First, I am very doubtful whether anyone connected with the management will be able to lecture very convincingly on economics to the trade unionist. Labour has its own views on economics, truly narrow and short-sighted in most cases, but honestly held and thoroughly believed in by the rank and file. The Communist Party realizes how difficult is the task of converting the adult, and holds Sunday Schools for the education of young Communists, and it is the bounden duty of the saner part of the community to combat this by teaching the elements of citizenship to the youngsters in the shops or indeed before they leave school. Secondly, while agreeing with the author, in the main, I should like to go farther than he in this direction. The training of boys for industry should have two aims:—(*a*) To convert the boy into an efficient workman, training hand and eye to perform operations quickly and accurately with the least possible effort, and at the same time offering him technical education opportunities which will lead to his advancement to the highest position his ability justifies; and (*b*) so to train his thinking and reasoning capacity and to give him such knowledge of affairs and men that life will not become the humdrum, drab existence towards which in these days of automatic and semi-automatic machines it is gravitating: in short, to teach him to live. It is surprising how much can be done and in what a short time in these directions if the work is entrusted to the right type of man, without which it is virtually useless, if not even harmful. The author deals with the more strictly educational aspect of this subject. I should like to see the efficiency of the men increased by the adoption of improved methods of actually training workmen, whether in special factories (as I think best); in "training bays" in charge of suitable instructors; or in the shops themselves. (See my article in *The Times Educational Supplement*, 19 August, 1922.)

**Mr. P. G. Pettifor** (*communicated*): I agree with the author that all possible steps should be taken to mitigate the dread of unemployment which, especially in times of trade depression, is a very real factor in reducing the efficiency of a workman, but I consider that an unemployment scheme would be more equitable if run by the electrical engineering industry as a whole rather than by isolated firms. Referring to the purchasing specifications, the use and issue of these should be carefully considered in each case. In my experience the use of such specifications has, in some cases, caused the cost of goods supplied to be unnecessarily high. Where everyday commercial products can be used, such specifications are not necessary.

**Mr. G. H. Nelson** (*in reply*): Referring to Mr. Mensforth's remarks regarding labour's knowledge of economics, there was no intention on my part of patronizing labour; on the contrary, I am anxious to encourage them to study economic questions and I still adhere to the contention in the paper that the majority of the workers have little or no knowledge of economics. This was particularly emphasized when one of the leading members of my works committee (who is also a member of one of the branches of the A.E.U.) passed a remark once at an open meeting that "one could not have prosperity without war." I agree with Mr. Mensforth's remarks that the proportion of labour in the cost of the product is often the smallest item, and I also agree that many factories pay more attention to the examination of the labour cost than to the other components; I therefore fully support his recommendation that equal attention be given to all sections. In regard to the estimating section, this is a part of the Mechanical Process and Rate-Fixing Department. I agree with his remark that a man of average ability should be able to earn $33\frac{1}{3}$ per cent bonus upon his basic rate and not upon his wages. This was not made clear in the paper. With regard to the fundamental basis of piecework that "prices must be the subject of agreement and mutual negotiations," this has been overcome in my case by arranging with the works committee to accept the principle and basis on which these prices are fixed. So far we have not come across any cases where disagreement exists beyond the point outlined in the paper. If one should arise it is referred to the management, in accordance with the general principle upon which the works are run, and, as demonstration is provided for, it is not likely to go beyond this stage in a properly managed works.

Mr. Mensforth and other speakers referred to the example given of the effect of increase of production on actual cost of an article. I will therefore deal with the point at this stage. In regard to Mr. Mensforth's remark that the factory expenses go up considerably more than the 25 per cent shown in the paper when the output is doubled, I quite agree with him there, but in the example given in the paper he has apparently overlooked the fact that a certain item of £3 000 for extra night work is shown separately instead of being included in the factory expenses, as it may be in certain cases. The factory expense in the example of the doubled output is therefore 75 per cent on labour, as against 100 per cent with the previous output. In examining the figures of the factory with which I am associated I find that the figure is more like 66 per cent, including overtime allowances.

With reference to Mr. Hurford's point in connection with selling expenses, although I do not discuss this question in the paper, I would say that from general experience one often finds that, with a small sale, selling expenses go up due to the extra effort that has to be put forward to endeavour to increase sales.

I entirely agree with Mr. Mensforth's remarks on works committees emphasizing the fact that where these committees have failed it has been largely due to the lack of the right sort of leadership by the employer ; his recommendation as to the constitution of the works committee coincides with my opinion. In regard to his suggestions in connection with engineering organizations, namely (1) production, (2) means of production, I think the two distinct parts recommended by him are fully covered in the paper.

With regard to Mr. Hurford's remarks *re* foremen's meetings, the foremen are encouraged to speak of their difficulties and the solutions suggested.

Replying to Mr. Higgs, I entirely agree with his recommendation of standardizing and specializing. Unfortunately, however, manufacturers in this country do not co-operate so as to compel the purchaser to accept a standard article, but rather, in order to make sure of effecting a sale, will often promise the customer anything. With regard to his question on piecework, I am a firm believer in piecework, because if day-work is standardized the best worker slows down to the speed of the slowest and special efforts are then necessary to increase the output of the factory by eliminating the slow workers, whereas in piecework the willing worker is on his own merits and can make as much as he likes, and therefore is not affected psychologically. In regard to his query about the basis of piecework, I am of the opinion that this should be time and not money, as this really is the basis of all calculations by the Rate-Fixing Department and the men in the shop. Concerning his remarks *re* the importance of detail on lists of material, it is the business of the Production Department to obtain the whole of the material, including detail parts.

Mr. Cowie asks for further information in connection with the Stores and Designing Departments. The Stores Department should come under the control of the Production Department, who are responsible for the fixing of all ordering levels and quantities and seeing that the material is there when required. The Production Department is also responsible for laying out the programme for the Design Department, i.e. the dates when drawings of various parts are required, and to see that these dates are kept.

Mr. Allen's remarks regarding the Purchasing Department are dealt with in my reply to Mr. Cowie. Referring to Mr. Allen's question *re* the arrangements that are made when operations in the shop are done in a different way from that laid down by the Process Department, this is taken care of by the time-study man in the shop. If the foreman is compelled to make a change in the process of operation for some reason or other, he obtains the services of the time-study man, who refixes the price for the new condition. This is referred to on page 344 of the paper as follows : " . . . or owing to the best machine for the operation not being available, then an additional piecework time fixed by the time-study man is allowed for the job, covering the excess time involved only." Mr. Allen asks for the percentage of office staff to workmen in the Rate-Fixing, Process and Production Departments. These are as follows :—

| Department | Percentage of Factory Cost | Percentage of Productive Payroll |
|---|---|---|
| Production . . . . . . | 0·65 | 3·4 |
| Technical and Mechanical Process Depts. . . . . | 0·65 | 3·4 |
| Inspection and Testing . . | 0·65 | 3·4 |

Referring to the sinking fund for unemployment, my idea is that each man should benefit by his own effort, and it should not be pooled. In connection with Mr. Allen's remarks regarding inspectors, in the works which I control, the inspectors are overlooking the men's work throughout the operations in the machine and on the floor, and every part is not taken to the inspector at a bench.

Major Brown raises the question of technical education. I may say that we have done all we can to improve the technical knowledge of our employees, but efforts in this direction are chiefly applied to the apprentices.

With regard to Mr. Richardson's remark about connecting up " Designing Department " with " Production " and " Designing " with " Process " in Fig. 1, naturally these departments co-operate very closely together, but I thought it unwise to make the diagram complicated by drawing and connecting up all the departments separately instead of showing them connected through the works management. The mere fact that they are shown connected through the latter, means that they should all co-operate and work together. With regard to the question of transport, this is generally under the control of the works superintendent. Although it is very important, I did not feel it necessary to describe the details. The question of keeping transport down to a minimum was very carefully considered in fixing the shop lay-out.

I entirely agree with Mr. Burnand's remarks regarding the running of a small business, and whereas all the detail which is necessary in a large business would be ruinous to a small one, at the same time I suggest that the same general principles should apply. I also agree with his point *re* efficient standardization. I thank Mr. Burnand for his suggestion that speeds of drills might be expressed in notches on the machine.

Referring to Mr. Baker's communication, I am very pleased to have the opportunity of supporting his contention that every effort should be made to combat the efforts of the Communist party, particularly its activities in the direction of proletarian Sunday Schools. We in our works have endeavoured to meet this by lectures to our boys in working hours, but a great deal more must be done. There are many sound thinking men giving their time to countering the Communists. The basis of the whole matter, as mentioned by Mr. Baker, is the teaching of the elements of citizenship and sportsmanship. After all no real sportsman can be a Communist.

## NORTH-WESTERN CENTRE, AT MANCHESTER, 23 JANUARY, 1923.

**Mr. W. J. Medlyn:** With the intensive development of industry and the mechanical aids to industry, scientific management is a subject of increasing importance, because where large numbers of men are employed the opportunities and possibilities of waste due to misdirected effort and lack of co-ordination or co-operation between the different departments are correspondingly great. One writer has stated that "the efficient utilization of labour will often overcome the handicap of poor equipment, and an engineer can have no greater asset than the aptitude to handle labour efficiently." This view agrees with one of the points made in the paper. I am not speaking with experience of ordinary industrial works, but in the South Lancashire District of the Post Office Engineering Department we have close on 2 000 workmen employed in the construction and maintenance of telephone and telegraph plant, and in a matter of this kind, although we are a Government Department, we are subject to the same economic laws and conditions which apply to a private industrial undertaking. We have a system of costing as regards the number of units of plant of various kinds which are constructed or maintained, but the organization required in a factory would not be applicable to our workmen, who generally have to be employed in more or less isolated small groups over a relatively wide area. It may be matter of common interest to mention that it was our practice some years ago to show these labour costs in terms of money values. The arrangement worked quite satisfactorily when the labour rates of pay remained fairly constant over a long period of time; but, following upon the outbreak of war, the rates fluctuated so much that it became impracticable to compare costs on that basis from year to year or over a number of years. I have no doubt that that condition would also apply generally to ordinary works management. The author stated that his firm's present practice is to use the man-hour basis of comparison. We overcame our difficulty in the same way; that is, our operations are now measured in terms of man-hours as well as money values. The author has referred to the advantages gained by a system of vocational training of workmen. In the Post Office we have this system in practice to a considerable extent, in co-operation with the local educational authorities. Evening classes are formed and the student normally attends twice a week. One evening is devoted to the teaching of the elementary theory of the subject, and the second evening to the teaching of the correct method of carrying out the practical work on which the student is normally employed. The students attend in their own time, but their railway fares (or tram fares) and class fees are paid by the Post Office. We have had these classes running successfully in Manchester and Liverpool, as well as in other parts of the country, for several years past. Taking the figures for the whole of the country, 1 364 students attended the classes during the session 1921–22, and 629, i.e. about 50 per cent, were awarded proficiency certificates. The cost was £1 3s. 6d. per student. In connection with the extension of our underground cable system we have required large numbers of cable jointers, and, as the ordinary step-by-step advancement was not rapid enough for this special requirement, we met the want by establishing jointing classes which the men attended in the department's time. In addition, pamphlets of an elementary and practical character covering every phase of the technical work carried out by the department have been printed, and such of those pamphlets as have a bearing upon a man's work are issued to him free of charge; 67 of these booklets, dealing with different subjects, have been issued, and altogether some thousands of copies have been distributed. It is interesting to note that those pamphlets are, in principle, somewhat similar to the works specifications which the author has explained. The pamphlets tell the man exactly what is the proper way of carrying out his work. Of course they are not quite so simple as the charts that were put upon the screen, but the principle is, I think, just the same. The drafting of these pamphlets was initiated by the Engineer-in-Chief of the Post Office at the end of the war. He called for volunteers among the members of the supervising staff who were experts in the various subjects; and, as a result of co-operative effort, the great bulk of the work was completed in about a year.

**Mr. G. E. Bailey:** The author has pointed out that, if we are to meet the world competition, it is necessary that all sections of an industrial organization should co-operate. I should like to go further and say that the firms should co-operate more than they do at the present time; in fact, they should do what they did during the war. Generally speaking, I agree with the author's views put forward in the paper. I recently attended a meeting where Mr. Brownlie, Chairman of the Amalgamated Engineers' Union, admitted that "ca' canny" was quite prevalent and that he himself had practised it. He went on to demonstrate that this was justified, and to point out to the employers that the remedy was largely in their own hands. In his opinion the chief cause was the workman's fear of unemployment. The author has put forward a scheme for dealing with this which has many good features, but I cannot say that it is going to meet the whole of the trouble. In the first place, his plan appears to depend absolutely on the super-bonus. Now it is common knowledge that generally (excluding special periods of unemployment such as we have now) the unemployed are the inefficient workers; so that, unfortunately, these people would not have been able to contribute towards the unemployment fund. Unless super-bonus went into a pool I do not quite see how the inefficient would benefit. I think that there is probably a lot to be gained by unemployment insurance by industry. This has been discussed by the Employers' Federation and it has been discussed by the unions, and I hope that shortly a concrete scheme will be put before us. I appreciate that it is a very difficult subject and the chief point will be, that whilst it enables a man to maintain his efficiency during unemployment it must also guard against malingering. The author points out the importance of co-operation betweer the drawing office and the works. I absolutely agree with that and I should like to go further. He referred to the effect upon manufacturing costs produced by lack of co-operation between these departments. Later on, unconsciously, he gave a very good lead. He pointed out in the production chart that the only unknown quantity was the first stage—obtaining the material. Obviously the obtaining of material depends to a great extent upon when it is ordered, and here I think is a clue which can be enlarged upon. Lack of co-operation between these two departments will result in information being supplied to the shops late, in the wrong sequence and intermittently and will, in turn, be responsible for late deliveries and increased work in progress. In connection with the foremen's meetings I should like to bring this out, that one of the chief advantages of these meetings is that the superintendent or the works manager gets the whole of his team together; he has representatives of every class of labour, and they sit down and discuss amongst themselves their own particular troubles—production, rate-fixing, labour questions, in fact everything that affects the efficiency of the workshop. In this way each department can compete, in a friendly way, with other departments for the purpose of obtaining the highest efficiency. In connection with rate-fixing, the author pointed out that all rates were fixed in the office. That is quite right for repetition work, but in a general shop it is impossible. I take it that in such a case the rate-fixer would fix prices in the workshop. There again he must satisfy himself that the methods available are the very best. If not, he should take it up at once with the other section, the Process Department, and have the job processed with a view to improving the efficiency and cutting down the cost of manufacture. On production I agree with the author except that I think he does not emphasize quite sufficiently that the improvement of any system of production depends absolutely upon the personal element. It depends upon the various departments and members of the staff honouring promises which they have made. Now, many systems can be evolved, many equally good, but all will fail without this co-operation and honouring of promises. Inspection generally is looked upon as seeing that the very best job is sent out, but I do not think that that is exactly the case. As a matter of fact the Inspection Department could sometimes save a lot of money by seeing that too good a job is not sent out. That may sound paradoxical, but the works must be run on commercial lines. As a matter of fact one of the chief reasons for the adoption of a limit system is that a man may not put too good a finish upon a particular job. He works to the limit that the designer fixes, based on his knowledge of what class of finish is necessary. If a 0·010-inch limit is good enough, it is waste of money for a workman to get down to 0·001 inch. That is where the inspector often comes in. Having agreed with the author on a good many things I am now going to disagree with him. He showed a chart illustrating how profits can be increased by 400 per cent. It is a very attractive scheme and I agree with the result, but I do not accept the methods of arriving at it. He did not explain the chart on the screen in the same way that he does in the paper. In the latter he compares moderate management in the workshop, bad management in the workshop, and efficient management in the workshop; but the total result, of course, is a combination of the whole work of the whole staff including the salesmen. I think that this is really meant by the author as a sort of camouflage bouquet for the Sales Department, because he demonstrates that the whole of the results obtained are due to the salesmen. I find that in the case of the 2 000-motor output the factory cost is £31 5s. and in the case of the 1 000 output it is only £32, so that there is only a difference of 15s. between the two shops. When we compare the final result it is £39 against £44, and the majority of that is made by the salesman, who sells 2 000 motors for £9 000 while the other sells only 1 000 for £8 000. I agree with the results, but in the way they are shown the whole of the blame is put on the shop as usual.

**Mr. L. H. A. Carr**: Before dealing in detail with specific points mentioned in the paper I would suggest that, taking the subject generally, one part of the question has not really been dealt with, namely, the question of works of medium or small size, of which there is quite a number in this country. In a works turning out a couple of thousand machines a year, say about 50 000 h.p., or even in a smaller works, it is probably impossible to use in its full extent a system such as that outlined in the paper. Such works need much more simplified systems. To take a single example, some reasons why they cannot go in for the Hollerith system were given in Mr. Lawrence's paper before the North-Western Students' Section last winter.* A small firm has one or two advantages which are lost in a large one. It is much easier to keep track of things, and also it is easier to bring the designers well into contact with, and more into a position of responsibility for, the various technical processes that have to be dealt with, the buying of materials, etc. That this lack of contact has been found to be a difficulty in large firms can be inferred from the fact that the author has so largely brought out the necessity for co-operation between the experts in the various departments concerned. But in any case the designer must have a good knowledge of all the technical processes and of the materials used. The excellence of a designer may, perhaps, be described as the amount which he knows of these other experts' jobs so that he is able to go the right way to meet them. In Fig. 1 several lines of co-operation are omitted. Perhaps that was in order not to make the diagram unwieldy, but the Technical Process Department and the Inspection Department must both work in co-operation with the designer. Another point which has scarcely been dealt with in the paper, but has rather been taken for granted, is the importance of the goods being right. It is no use having a works where things can be manufactured beautifully and cheaply and salesmen who can sell them, if the job is not right when it is done. Although the author has mentioned some of the attributes which he thinks a works manager should possess, he appears to have taken it for granted that the designer is absolutely perfect. In costing, an important point which has to be watched is the accuracy with which the work-people in the shop book their time on the right job. Inaccuracy in that respect has in the past caused trouble in working out a good many costs. It is essential that the men in the shop should put the costs down to the right job, because that is really the foundation of the costing system. If that is not done no cost system can give correct results. The author has given us a case where a bracket was improved by co-operation. Personally I am inclined to say that the designer was to a large extent responsible for turning out a poor design. If he did not know what was the best design it was his business to find out by co-operation. Such faults may be overcome to a certain extent by utilizing better-class men, and the whole question of what quality of engineers and draughtsmen are used for certain jobs is mixed up with this question. If all engineers and draughtsmen were perfect there would not be nearly so many troubles, but the majority are not perfect. Possibly salaries are not sufficient. One cannot always afford to put the best class of man on some of the smaller work, and in design offices it would appear to be necessary to balance the amount that can be spent on the staff against the cost of the mistakes which a less-skilled staff will make. In regard to the question of committees it must not be overlooked that whatever committees are formed, they must be set up in such a fashion as not to destroy responsibility. Responsibility for any job must still be kept in the right place. On page 341 the author has said: "Success depends largely on one's executive acumen, initiative and ability to co-operate." I would add that, in addition, hard work is absolutely necessary. With regard to the accusation that the designer sometimes fails to give to the works full information by the date required by the Production Department, that is very often the customer's fault. I would suggest to members who may have to influence orders, or are consulted with regard to orders, that they can get much better service if they will give all the necessary information when the order is placed. The type of thing I have in mind is the case where a consulting engineer will not settle what cables he is going to have until the job is nearly finished, his attitude being: "It does not matter, the terminal box is the last bit which will be put on the machine." It does matter. It holds up the whole business, the drawing office cannot complete their part of the work, neither can those responsible for ordering the material. I think that probably those outside manufacturers' works cannot have any conception of the extra work and worry on their particular orders if information is held back like that. The lay-out of the shop has not been discussed in the paper. Needless to say, it is of great importance. Further, however well the shop may be laid out when it is first built, extensions and alterations are almost bound to take place afterwards. It is to be regretted that this question has not been dealt with in the paper. The author has not dealt with the difficulty of arranging that the work which comes into the shop does not include too high a proportion of machines of a particular type. For example, a large machine tool may be sufficient to deal in a year with an average year's work. But suppose all the orders necessitating the use of that machine tool are not spread over the whole year, but happen to be received in a single month; would the tool be sufficient?

---

* *Journal I.E.E.*, 1923, vol. 61, p. 52.

**Mr. A. B. Mallinson**: To my mind the personal element is one of the most important factors in the whole thing, and I think that in Fig. 3 the author has unconsciously shown a very clear example of the personal element as it exists. That figure shows four curves, and we find in each a drop in production for July. That, I think we can assume, is due to holiday stoppages. The surprising thing, however, is that the dotted line showing the rejects is practically steady. There we have got the personal element. The amount of work coming before the tester has decreased; therefore he inspects rather more thoroughly and the result is a straight line. Another point that I have come up against very often, and upon which manufacturers feel very strongly, has only been casually mentioned in the paper. When we have got a job completed we want to get it out of the works at once. Do not let the workman see it standing about for some time if he has been told that it was wanted in a hurry. During all the time that the job is going through there is need for co-operation between the salesman and those who are working to get the job completed in a promised number of weeks. I would emphasize the great importance of good feeling between master and men, and particularly between every department of staff. As the author has pointed out in one of the slides, it is the saving on the whole job that tells at the finish. Although the amount may be very small in each individual operation, they all count up in the end, and it is that which enables the seller to influence the customer and secure the order.

**Mr. R. Townend**: Having had some experience of the actual working of the system of works production described in the paper, I can agree with the author as to its advantages, but of course the extent to which it can be adopted depends largely upon the size of the factory. I fully agree that the closest co-operation is necessary between the engineering department, drawing office and shops, if economical production is to be obtained, and the lack of this co-operation is illustrated by the example of the motor end-bracket mentioned by the author. It would appear at first sight that the responsibility for the complicated design rested upon the draughtsman, but I consider the pattern-maker to be even more to blame. The former did not appreciate that the design was complicated, but the latter knew that it was, and ought to have taken steps to have the design simplified. Whilst I agree that in the case of complicated designs it is necessary that these should be considered at a meeting of the designer and manufacturer, it would be quite impossible to apply this to each part of a piece of apparatus, as advocated by the author.

**Mr. T. E. Herbert**: Some ten years ago I submitted a paper on scientific management to the Institution of Post Office Electrical Engineers and the time which has elapsed has confirmed my opinion, for what it is worth, that the basic principles are unassailable. The present paper may be described, I think, as a description of the author's methods of applying scientific management to his works' problems. Taking a really broad view of the subject, I think he has laid down a few fundamental propositions which, if carried into effect, will produce the organization he has described. Such fundamental principles seem to me to be those of Dr. Taylor. First of all, functional organization, secondly, process instructions, which obviously involve time and motion study, and thirdly the time-table. I should imagine that the time-table is one of the most important things; so far as my problems are concerned it is undoubtedly so. The main object I take it is to obtain the maximum results with the least effort, which is merely another definition of efficiency, or alternatively the elimination of waste. The human element of the problem is rightly stressed, and the absolute necessity of obtaining full co-operation is appreciated. It seems to me that the human element is dealt with by a system of payment by results, and an endeavour to eliminate suspicion by dealing quite openly and quite fairly with the worker, but I would venture at this point to offer a word of friendly criticism. I am disposed to think some of the author's introductory remarks are of somewhat doubtful validity, and that the argument should have been carried a good deal further or he should merely have taken his stand upon getting results with the minimum of effort, in other words on the attainment of efficiency. For example, some of his remarks are in conflict with the teaching of the Manchester School of Economics in regard to buying in the cheapest market and selling in the dearest. If that principle, so stated, is sound the worker ought to give as little as he dare for as much as he can possibly exact. Either both those propositions are sound or they are both unsound. I do not propose to carry that point any further, but I would say that the fascination of the fundamental idea of Taylor's system to me is that it is a practical method of substituting co-operation and help for the mere driving methods which have been so unintelligently adopted in a good many factories in the past, and perhaps even to-day. Here again I am convinced that the true rectification of most of our troubles lies in the attainment of efficiency in general. Some remarks have been made on selling efficiency, but not merely do we want efficiency in the factory, we also want it in finance and in distribution. I will not pursue that subject further, but I will suggest that nothing essentially wrong can persist, and that waste seems to be the deadly sin which carries the most severe penalties. I would ask the author to look at the appalling inefficiency of finance and distribution and appreciate that the engineer has a problem to solve which nobody else seems to be willing to tackle. That is why the remarks recently made by the President, and reiterated in this paper, on the study of economics are of such vast importance. It is of little use to obtain splendid results in the factory if the other processes are scandalously inefficient. One speaker touched upon the point that cost accounting, which involves an elaborate system of records, depends on the accuracy with which the worker fills up his time sheet or whatever equivalent is in use. I was rather interested to realize that we were not the only people who had a certain amount of difficulty in getting precisely accurate information on bits of processes. The Whitley Committee has helped us in those matters by impressing on the members of the staff the desirability and the reason why we want these things in detail. These committees have, too, been exceedingly valuable to us in removing suspicion and in attaining that healthy spirit of cheerful co-operation which is the goal of the much-maligned idealist.

**Mr. G. H. Nelson** (*in reply*): I was very pleased to have Mr. Medlyn's contribution to the discussion, and was particularly gratified to know that a Government department has established a system somewhat on the lines of that outlined in the paper.

With regard to Mr. Bailey's comments, I heartily endorse his suggestion that in addition to the co-operation inside an industrial organization, it should extend outside between firms. I may say that during my visit to the States recently I found this very prevalent and was particularly struck with the free way in which I was taken round the American works and had various processes explained to me, in spite of the fact that I represented a competitor. I endeavoured to give *quid pro quo.* I consider it the duty of all Englishmen who visit the States to deal with the Americans in this frank manner, as by this the feeling between the countries can be improved considerably and the power of America and England together increased and directed in the way of preventing a recurrence of calamities of the terrible nature of the Great War, which after all is the real cause of the suffering and unemployment at the present time.

In connection with unemployment, I agree with Mr. Bailey that the Government scheme of unemployment insurance by industry is sound, and I do not suggest that the scheme outlined in my paper should replace this, but it should be in addition to the Government scheme, the latter being that which is necessary to enable men to exist when out of work, whereas my scheme is with the object of encouraging men to work and give their best to provide something in addition to Government allowance. In connection with the Rate-Fixing Department, in the works with which I am connected the whole of the drawings—even for odd jobs—go to the Rate-Fixing Department and are processed. This does not just refer to repetition work, as suggested by Mr. Bailey. I am sorry that he does not think that I emphasized sufficiently the personal element. There is no doubt that the success of any system in a works is absolutely dependent on the human element. No matter how good the system is, if the will to work is not there it will be a failure, and the object of works committees, foremen's meetings, and the careful selection of heads of departments, as emphasized in the paper, is the endeavour on the part of the manager to get the team of the best personnel to co-operate and make the system a success. In connection with the necessity of seeing that too good a job is not made, we endeavour to take care of this in the Rate-Fixing Department by specifying on the process sheet the class of finish that is required, and the price is fixed accordingly. In addition, as mentioned in the paper, we mark our drawings with different colours, to show the differences in finish. With regard to Mr. Bailey's remarks regarding the credit for increased output going to the salesmen, I am afraid that I rather look at the question from the opposite view, namely, that the works are so efficiently run that it is not possible to make any great improvement, whereas by ensuring that we get the proper results from the necessary selling expenditure, great economies arise.

In connection with Mr. Carr's remarks regarding the running of small works, I must say from my experience of large works that I am of the opinion that small works run on the same basic principles, as outlined in the paper, can obtain greater efficiency than the larger organizations, the reason being that the number of personal elements is smaller and therefore more easy to handle. As mentioned before, I still feel that the same principles should be applied, with of course the application of the right common-sense of the management as to the details required. With regard to the booking of time in the shop, I agree with Mr. Carr that it is difficult to get 100 per cent efficiency in this direction, but this is taken care of by arranging for a clerk to book all the details on the time sheet under the control of the Rate-Fixing Department and the man only fills in the time. I am glad that Mr. Carr agrees with my view that the Design Department should co-operate as far as possible with all people likely to be interested in the design of a machine. I agree with his remarks in regard to responsibility. On no account must responsibility be divided by the committee system. It is very easy for it to become so, but the insistence on this by the management can prevent it. For instance, in the works where this system is in operation the foreman is not allowed to try to shelve the responsibility for bad work on to the Inspection Department. It is solely the foreman's mistake for having allowed the bad work to be produced. I agree with Mr. Carr that customers can help very considerably by giving full information when the order is placed and by immediately giving a decision in regard to any question which may arise. The matter of shop lay-outs has not been discussed in the paper, because my object has been rather to describe a system than to go into the details of a lay-out, and to encourage existing works to install the system where plant already is in operation, rather than to deal with new factories where the plant can be laid out for ideal conditions. On the other hand, however, even a shop laid out ideally to-day may not necessarily be ideal for the product manufactured in 20 years' time. In connection with Mr. Carr's remark regarding the laying-out of various operations in the shop, the system outlined in the paper enables this to be done very conveniently, because by assembling charts (similar to Table 3) of all the machines produced in any month and so arriving at the total number of machining hours, one can see ahead whether the plant can deal with the output it has to produce, and, if not, then steps can be taken to get outside help where the shortage of machinery exists.

I was glad to hear Mr. Mallinson's recommendation that customers should endeavour to take plant at the time it is completed, especially when they insist on their delivery date. Unfortunately, we have found in many cases that a purchaser has been most emphatic about his delivery date, special pressure has been put on all departments to keep this date, and when it has been kept the machine has remained in the shop for weeks and sometimes months. Customers should realize that the moral effect is very bad.

Referring to Mr. Herbert's contribution to the discussion, I notice that he mentions the principles of Dr. Taylor, who, in my opinion, unfortunately calls this system "scientific management." The bare mention of the word "scientific" frightens a great many of the old-fashioned type of employer. That is one reason why this word is left entirely out of the paper. I also support Mr. Herbert's contention that we want efficiency in finance and distribution, and I trust that some experts on these subjects will give us the benefit of their recommendations, as suggested in the paper.

In conclusion I should like to thank all those who have taken part in the discussions for their constructive suggestions, and I sincerely hope that the object which I had in giving the paper will be fulfilled, namely, that those responsible for the management of works will consider such general principles outlined in the paper as are applicable to their own works and apply them where they do not exist, thus helping to reduce production costs and to develop industry, which will eventually result in a considerable reduction of unemployment.

# THE RATING OF CABLES FOR INTERMITTENT OR FLUCTUATING LOADS.*

By S. W. Melsom, Associate Member, and H. C. Booth.

[From the National Physical Laboratory.]

(*Paper first received* 31*st January, and in final form* 27*th December,* 1922.)

Summary.

The extent to which the rating of a cable is affected by an intermittent or fluctuating load as compared with continuous running conditions is investigated theoretically, and formulæ are given by means of which the effect of any type of loading can be calculated.

It is shown by experimental determinations on various sizes and types of cables that the thermal time-constant can be calculated either from a heating or cooling curve of a particular cable, or from the specific heat and mass of the various components of the cable.

Tables are given showing the rating for the cables for which load tables are given in the I.E.E. Wiring Rules, on the same basis as for motors, i.e. ½-hour and 1-hour ratings.

The question of the permissible current in cables used for supplying motors or other gear for such purposes as cranes, winches or hoists where the period of full-load current may be comparatively short, alternating with periods when the motor is running light or is shut down, was raised by the Ship Electrical Equipment Committee of the Institution.

Goldschmidt † investigated the case of motors used for such work, and stated that long experience in actual practice has proved that in nearly every case a motor which stands a 1-hour test with a moderate temperature-rise is large enough for crane work. In modern practice, motors for such purposes are rated at ½ hour and 1 hour, depending on the conditions of use.

In the case of cables the time required to attain the maximum temperature is, as a rule, very much shorter than with motors, and it is necessary to consider them separately in order to ensure that the combination of motor and cable will be suitable for a given purpose.

In a previous paper (*Journal I.E.E.*, 1911, vol. 47, p. 711) the authors gave some results showing the order of increased rating that could be used for cables under intermittent load, the periods of variation being a few minutes, as would be the case in the actual use of a motor. These and other observations have been used in what follows.

For the mathematical treatment of the problem let:—

$w$ = rate (in watts) of heat transmission through unit length of the covering of the cable for each degree C. of temperature excess above the surrounding air;

$c$ = heat capacity of unit length of cable per degree C. in watt-second units (joules);

$q$ (or $Q$) = rate (in watts) at which energy is being developed in unit length of the cable;

$\theta$ = temperature excess (referred to in the calculations below, for brevity, as "temperature");

$t$ = time in seconds.

Then, if we assume that the heat dissipation is proportional to the temperature excess at any moment:—

$$qdt = cd\theta + w\theta dt$$

or

$$\left(\frac{w}{c}\right)dt = \frac{d\theta}{(q/w - \theta)}$$

Integrating, $$\left(\frac{w}{c}\right)t = -\log_e(\theta - q/w) + \log_e P$$

where $P$ = a constant of integration;

whence $$e^{wt/c} = \frac{P}{\theta - q/w}$$

To find $P$, assume that when $t = 0$ the temperature $\theta$ has the initial value $\theta_1$, then

$$P = \theta_1 - q/w$$

$$e^{wt/c} = \frac{q/w - \theta_1}{q/w - \theta}$$

whence $$\theta = e^{-wt/c}(\theta_1 - q/w) + q/w$$

If the cable runs for $a$ seconds at $Q$ watts, starting at an initial temperature $\theta_2$, let the temperature attained be

$$\theta_1 = e^{-wa/c}(\theta_2 - Q/w) + Q/w$$

If the cable then runs for $b$ seconds at $q$ watts, starting at an initial temperature $\theta_1$, let the temperature attained be

$$\theta_3 = e^{-wb/c}(\theta_1 - q/w) + q/w$$

and if then $\theta_3 = \theta_2$ we have

$$\theta_1 = \frac{(Q/w)(1 - e^{-wa/c}) + (q/w)(1 - e^{-wb/c})e^{-wa/c}}{1 - e^{-(a+b)w/c}}$$

Or, since $Q/w = M$, the maximum temperature attained when running continuously at $Q$ watts, and $q/w = m$, the maximum temperature attained when running continuously at $q$ watts, and writing $\gamma$ for $c/w$, where $\gamma$ is the thermal time-constant of the cable,

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1905, vol. 34, p. 660.

$$\theta_1 = \frac{M(1 - e^{-a/\gamma}) + m(1 - e^{-b/\gamma})e^{-a/\gamma}}{1 - e^{-(a+b)/\gamma}}$$

Taking the case of a cable running under crane-load conditions where the motor runs at full load for $a$ minutes and at light load for $b$ minutes, and so on, intermittently for a long period, the increased rating for the same temperature-rise as would be attained if the cable were loaded continuously at its normal continuous rating of $I$ amperes, can be calculated as follows :—

Let $i$ be the current on light load and $si$ the maximum load current, $s$ being the ratio of the maximum to the light-load current.

Taking the general case of temperature elevation under a fluctuating load of this kind, we have

$$\theta = \frac{M(1 - e^{-a/\gamma}) + m(1 - e^{-b/\gamma})e^{-a/\gamma}}{1 - e^{-(a+b)/\gamma}}$$

If the watts developed by $i$ amperes be $q = i^2r$, where $r$ is the resistance of unit length of cable at the maximum temperature, then with $si$ amperes the watts developed will be $q = s^2i^2r$. We have therefore

$$M = \frac{s^2i^2r}{w} \quad \text{and} \quad m = \frac{i^2r}{w}$$

and the maximum temperature elevation will be

$$\theta = \frac{i^2r}{w}\left[\frac{s^2(1 - e^{-a/\gamma}) + (1 - e^{-b/\gamma})e^{-a/\gamma}}{1 - e^{-(a+b)/\gamma}}\right]$$

The maximum temperature elevation for continuous running with $I$ amperes will be $I^2r/w$, and this must equal $\theta$, whence we obtain—

$$si = Is\sqrt{\left[\frac{1 - e^{-(a+b)/\gamma}}{s^2(1 - e^{-a/\gamma}) + (1 - e^{-b/\gamma})e^{-a/\gamma}}\right]}$$

or if $si = nI$, where $n$ is the rating factor, we have

$$n = s\sqrt{\left[\frac{1 - e^{-(a+b)/\gamma}}{s^2(1 - e^{-a/\gamma}) + (1 - e^{-b/\gamma})e^{-a/\gamma}}\right]}$$

Thus, if the cable were rated to run at 200 ($= I$) and if $a = 4$ minutes (240 secs.), $b = 6$ minutes (360 secs.), $\gamma = 1\,300$ seconds, and $s = 2$, then

$$n = 2\sqrt{\left[\frac{1 - e^{-600/1\,300}}{2^2(1 - e^{-240/1\,300}) + (1 - e^{-360/1\,300})e^{-240/1\,300}}\right]}$$

$= 1{\cdot}304$, and the maximum permissible current during the full-load period is

$$si = 1{\cdot}304 \times 200 = 261 \text{ amps.}$$

A simpler problem arises out of the decision of the I.E.E. Committee that cables should be rated on the same basis as the motors used, i.e. at a ½-hour and 1-hour rating. For the calculation of the rating factor to suit these conditions only the initial part of the appropriate heating curve need be considered.

On the assumptions made, the temperature of a cable as deduced from the general equation, at any time $t$ after switching on, will be

$$\theta = M(1 - e^{-t/\gamma})$$

where $M$ is the maximum final temperature.

Let $M_0$ be the final permissible maximum temperature attained when running with the rated current $I_0$. To a first approximation

$$M_0/M = (I_0/I)^2$$

therefore $\theta = M_0(I/I_0)^2(1 - e^{-t/\gamma})$

whence $I = \dfrac{I_0\sqrt{(\theta/M_0)}}{\sqrt{(1 - e^{-t/\gamma})}}$

If $I$ is greater than $I_0$, but $\theta$, the temperature attained after the interval $t$, is not to exceed $M_0$, we have for the rating factor $n$ :—

$$I = I_0\frac{1}{\sqrt{(1 - e^{-t/\gamma})}}$$

or $n = \dfrac{1}{\sqrt{(1 - e^{-t/\gamma})}}$

For the ½-hour rating, $t$ is 1 800 seconds, and for the 1-hour rating, 3 600.

It will be seen that these formulæ require that the thermal time-constant $\gamma$ should be known. This quantity is the ratio of the heat capacity of the cable to the rate at which heat, measured in the same units, would be transmitted from the cable if the temperature excess were 1 degree C. Regarded from another point of view it is the time that would be required for the cable to reach the maximum temperature corresponding to any current if, with this current passing through the cable, all dissipation of heat to external space were prevented and the heat generated by the current were applied solely to heating the cable.

Thus, if $M$ be the maximum temperature excess attained when the current is running at $Q$ watts, and if $c$ be the heat required to raise the temperature of the cable 1 degree C., then the heat capacity of the cable when raised in temperature $M$ degrees is $Mc$. When it has reached its maximum temperature corresponding to the current carried, and conditions have in consequence become stationary, the heat dissipated per second by the cable, $wM$, is equal to the heat generated, i.e.

$$wM = Q = I^2r$$

where $r$ is the resistance and $I$ the current. Therefore the time required to reach the maximum temperature $M$, if no heat were radiated from the cable, would be

$$\frac{Mc}{Q} = \frac{Mc}{Mw} = \frac{c}{w} = \gamma$$

a quantity which is therefore defined as the " thermal time-constant " since it will be the same whatever maximum temperature be considered.

The thermal time-constant of a cable can, therefore, be approximately calculated if we know the weight and specific heats of its various components and the final temperature-rise corresponding to a given current.

The temperature of the core will be generally higher than that of the surrounding layers of insulating and other materials. If in order to simplify the calculation it be assumed that the whole of the cable attains the temperature of the core, it would seem as if the value of the thermal time-constant calculated on this assumption should be somewhat in excess of its true value. This error would, however, appear to be very largely compensated for by the fact that in practice a cable is not freely suspended in air, but is in immediate contact with some support, which also shares to some extent in the temperature-rise of the cable. A comparison of the results obtained by calculation of the constant from the dimensions and thermal quantities of the cable with those obtained by the more direct experimental method next to be described would seem to indicate that, within the limits of accuracy required in the evaluation of the constant, the first method affords a satisfactory approximation.

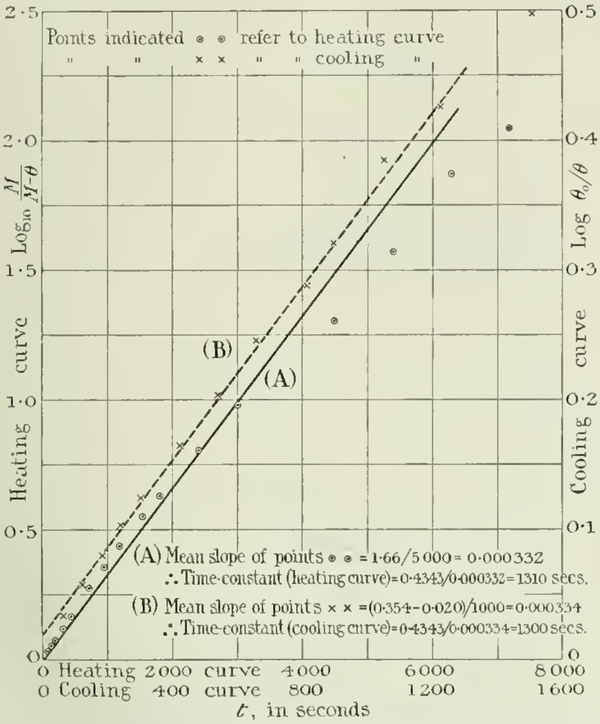


FIG. 1.—Determination of the time-constant of a 19/14 S.W.G. rubber-covered cable by means of the heating and cooling curves.

For the calculation of the thermal time-constant from the heating curve we can proceed as follows:—

Since at any time $t$ after switching on, the temperature excess

$$\theta = M(1 - e^{-t/\gamma})$$

where $M$, as before, is the final maximum temperature, we have

$$\log_{10}\left(\frac{M}{M-\theta}\right) = t\frac{(0\cdot4343)}{\gamma}$$

If a series of values of $\theta$ are available for various time intervals after switching on, and if we know $M$ the maximum final temperature, then, on plotting the values of $\log_{10}[M/(M-\theta)]$ derived from the values of $\theta$, against corresponding values of $t$, we should obtain a straight line passing through the origin, the slope of which line should be equal to $0\cdot4343/\gamma$. This affords a criterion as to how nearly the heating curve follows the exponential law here assumed, and also, if the slope be measured in the proper units, a means of evaluating the constant $\gamma$.

In practice, however, this particular method is somewhat difficult in application. Values derived from the first part of the heating curve are liable to error because here the temperature is changing very quickly. In the initial stages of the heating curve the temperature of the core will also be considerably higher than that of the covering, and this would tend to make the value of the thermal time-constant derived from this part of the curve too low.

For the latter part of the curve when $\theta$ is approaching its limiting value $M$, the term $(M-\theta)/\theta$ becomes uncertain, since $(M-\theta)$ is the difference of two nearly equal quantities, one of which, $M$, requires a very long and careful observation for its exact determination.

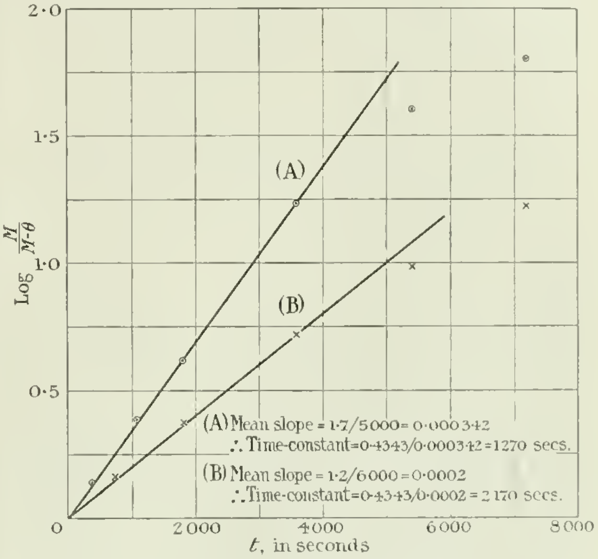


FIG. 2.—Determination of the time-constant of two lead-covered paper-insulated cables:

(A) 0·1 sq. in. single. (B) 0·1 sq. in. concentric.

For this reason, therefore, it is preferable to use the cooling curve. For this we have $\theta = \theta_0 e^{-t/\gamma}$, where $\theta_0$ is the initial temperature for $t = 0$. From this it follows that

$$\log_{10}(\theta_0/\theta) = (t/\gamma)\log_{10} e = 0\cdot4343t/\gamma$$

so that if a series of values of $\log_{10}(\theta_0/\theta)$ be plotted against $t$, a straight line passing through the origin should be obtained the slope of which should again be equal to $0\cdot4343/\gamma$.

As this does not necessitate the determination of the maximum temperature it is generally the more convenient method.

Some illustrative examples of these three methods of determining the thermal time-constant will now be given. They will also serve to show the sort of consistency obtainable by the various methods and to what extent it is permissible to rely on a calculation of the thermal time-constant derived from the dimensions and specific heat of the cable in place of determinations based on the characteristics of the heating or cooling curves as obtained by direct experiment.

*Example* (1). *A rubber-covered* 0·094-*sq. in. cable.*—In Fig. 1 the values of $\log_{10}[M/(M-\theta)]$ are shown plotted against time for (A) the heating curve, and of $\log_{10}(\theta_0/\theta)$ for (B) the cooling curve.

The slope of the best mean straight line through these points has been measured and the constant, $\gamma$, obtained by dividing 0·4343 by the slope. The values are:—

(*a*) Heating curve $\gamma = 1\,310$ seconds.
(*b*) Cooling curve $\gamma = 1\,300$ seconds.

The evaluation of the thermal time-constant of this cable by means of the dimensions and specific heat is as follows:—

The total heat capacity of the cable is here the sum of two components:—

(1) The heat capacity of the conductor based on weight of copper × specific heat = 2·135 watt-seconds.
(2) The heat capacity of the covering, rubber and braiding = 2·79 watt-seconds.

Hence $c$, the total heat capacity per cm, = 4·925 watt-seconds.

The value for the covering is derived from a direct determination of the specific heat of rubber and braiding made on a small sample taken from the cable. The actual value obtained was 0·39 calorie (= 1·63 watt-second units) per gramme per degree C., and is subject to a possible error of ± 3 per cent. The heat capacity of the covering is obtained by multiplying the value of the specific heat, given above, by the weight of the covering per unit length of cable, which weight was determined on a length of about a yard of covering.

The resistance of unit length of conductor of the 0·094-sq. in. cable at 15·6° C. was $2\cdot86 \times 10^{-6}$ ohms, and since for a current of 169 amperes maintained continuously there was a temperature-rise of 21·8 degrees C., the resistance at the higher temperature is

$$r = [1 + (0\cdot004 \times 21\cdot8)]\,2\cdot86 \times 10^{-6} = 3\cdot11 \times 10^{-6}\ \text{ohm/cm}$$

Hence

$$I^2r = wM = 3\cdot11 \times 10^{-6} \times 169^2 = 8\cdot83 \times 10^{-2}\ \text{watt}$$

and
$$w = \frac{8\cdot83 \times 10^{-2}}{21\cdot8} = 4\cdot06 \times 10^{-3}\ \text{watt}$$

Thus the thermal time-constant

$$\gamma = c/w = 4\cdot925/(4\cdot06 \times 10^{-3}) = 1\,210\ \text{seconds.}$$

*Example* (2). *A lead-covered paper-insulated single* 0·1-*sq. in. cable* [*see Fig.* 2 (A)].—Only the heating curve was available. The value deduced from the slope of the plotted values of $\log_{10}[M/(M-\theta)]$ was $\gamma = 1\,270$ seconds.

For the total heat capacity of unit length of cable we have:—

| | | |
|---|---|---|
| (1) Conductor .. | 2·14 | watt-sec. units. |
| (2) Lead covering .. | 1·59 | ,, ,, |
| (3) Paper and oil .. | 1·62 | ,, ,, |
| Total heat capacity $c$ = | 5·35 | ,, ,, |

$$w = \frac{I^2r}{M} = \frac{200^2 \times 2\cdot79 \times 10^{-6}[1 + (0\cdot004 \times 30)]}{30} = 4\cdot16 \times 10^{-3}\ \text{watt}$$

Therefore

$$\gamma = c/w = 5\cdot35/(4\cdot16 \times 10^{-3}) = 1\,290\ \text{seconds}$$

Here again the values for the impregnated-paper insulation were derived from a determination of the specific heat of a sample taken from a cable, the actual values being—

0·37 calorie (= 1·54 watt-second units) per gramme per degree C.

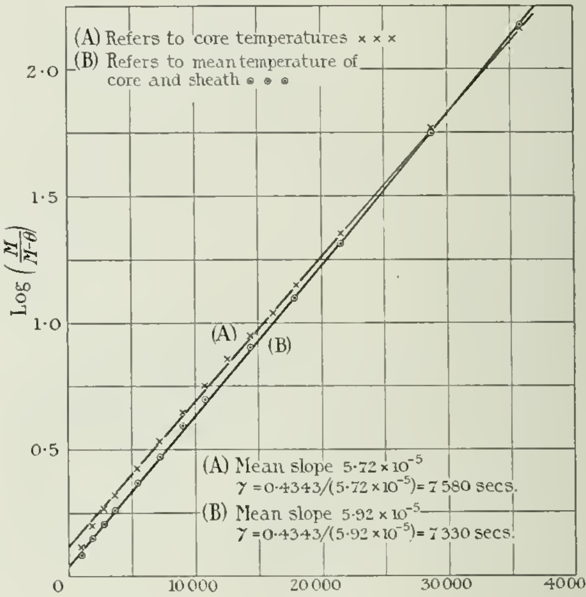


FIG. 3.—Determination of the time-constant of a high-tension three-core paper-insulated cable with lead covering and armouring.

*Example* (3). *A lead-covered paper-insulated concentric* 0·1-*sq. in. cable* [*see Fig.* 2 (B)].—Only the heating curve was available. The value deduced from the slope of the plotted values of $\log_{10}[M/(M-\theta)]$ was $\gamma = 2\,170$ seconds. In this case $\theta$ was the mean value of the temperature-rises of the inner and outer conductors, respectively.

For the total heat capacity of unit length of cable we have :—

| | | | |
|---|---|---|---|
| (1) Conductor (inner and outer) | 4·27 | watt-sec. | units |
| (2) Lead covering . . . . | 2·77 | ,, | ,, |
| (3) Paper and oil . . . . | 4·93 | ,, | ,, |
| Total heat capacity per cm $c =$ | 11·97 | ,, | ,, |

$$w = \frac{I^2 r}{M} = \frac{2 \times 170^2 \times 2\cdot7[1 + (0\cdot004 \times 30\cdot6)]10^{-6}}{30\cdot6}$$

$$= 5\cdot72 \times 10^{-3} \text{ watt}$$

Therefore

$$\gamma = c/w = 11\cdot97/(5\cdot72 \times 10^{-3}) = 2\ 100 \text{ seconds}$$

*Example* (4).—*A high-tension 3-core paper-insulated armoured cable on which a number of heating curves both of core and lead sheath were taken, special attention being directed to accuracy of the intermediate observations on the curve.*—In Fig. 3 are plotted the values of $\log_{10}[M/(M - \theta)]$ against time, (A) referring to the temperature of the core only, and (B) to the average temperature of core and sheath. The values of the thermal time-constant are 7 580 seconds from curve (A), and 7 330 seconds from curve (B), as against the value of 7 100 seconds deduced from the dimensions and thermal constants of the components of the cable. In calculating the heat capacity, the effect of the armouring has been ignored since it is separated from the lead sheath by tape and obviously cannot be regarded as adding appreciably to the heat capacity of the cable.

TABLE 1.

| Cable size (Nominal) | Thermal time-constant | | Multiplying factor for rubber | | Multiplying factor for paper | |
|---|---|---|---|---|---|---|
| | Rubber | Paper | ½-hour rating | 1-hour rating | ½-hour rating | 1-hour rating |
| sq. in. | secs. | secs. | | | | |
| 0·0145 | 520 | 700 | 1·02 | 1·00 | 1·05 | 1·00 |
| 0·0225 | 600 | 760 | 1·03 | 1·00 | 1·06 | 1·01 |
| 0·04 | 890 | 900 | 1·07 | 1·01 | 1·09 | 1·01 |
| 0·06 | 1 090 | 1 050 | 1·11 | 1·02 | 1·12 | 1·02 |
| 0·075 | 1 350 | 1 150 | 1·17 | 1·04 | 1·15 | 1·03 |
| 0·1 | 1 520 | 1 320 | 1·21 | 1·05 | 1·18 | 1·04 |
| 0·12 | 1 630 | 1 430 | 1·23 | 1·06 | 1·20 | 1·05 |
| 0·15 | 1 820 | 1 600 | 1·26 | 1·08 | 1·23 | 1·06 |
| 0·2 | 2 190 | 1 850 | 1·34 | 1·11 | 1·27 | 1·08 |
| 0·25 | 2 440 | 2 070 | 1·38 | 1·14 | 1·32 | 1·10 |
| 0·3 | 2 810 | 2 250 | 1·46 | 1·18 | 1·36 | 1·13 |
| 0·4 | 3 390 | 2 620 | 1·57 | 1·24 | 1·43 | 1·17 |
| 0·5 | 3 690 | 2 925 | 1·61 | 1·27 | 1·49 | 1·20 |
| 0·6 | 4 060 | 3 185 | 1·67 | 1·30 | 1·54 | 1·23 |
| 0·75 | 4 100 | 3 520 | 1·68 | 1·31 | 1·60 | 1·26 |
| 1·0 | 4 510 | 3 970 | 1·74 | 1·35 | 1·66 | 1·30 |

In the first example there is a difference of about 7 per cent between the two determinations, which, however, is not large when the difficulties of the various measurements are taken into account. It is, of course, possible that the difference arises from the fact that the two methods of determination apply to conditions that are not strictly comparable. The heating or cooling curve refers to a cable in contact with the floor (the effect of which is nearly equivalent to that of a wood casing or iron pipe), whereas the calculation from the dimensions and specific heats of the constituent parts of the cable leaves this factor entirely out of account.

TABLE 2.

| Cable size (Nominal) | Permissible current | | | Size of cable that will carry same current as for continuous rating, but for :— | |
|---|---|---|---|---|---|
| | ½-hour rating | 1-hour rating | Continuous rating as in I.E.E. Wiring Rules | (1) ½ hour | (2) 1 hour |
| | | | *Rubber cables.* | | |
| sq. in. | amps. | amps. | amps. | sq. in. | sq. in. |
| 0·0145 | 38 | 37 | 37 | 0·0145 | 0·0145 |
| 0·0225 | 47 | 46 | 46 | 0·0225 | 0·0225 |
| 0·04 | 68 | 65 | 64 | 0·04 | 0·04 |
| 0·06 | 92 | 85 | 83 | 0·06 | 0·06 |
| 0·075 | 113 | 101 | 97 | 0·075 | 0·075 |
| 0·1 | 142 | 124 | 118 | 0·1 | 0·1 |
| 0·12 | 160 | 138 | 130 | 0·1 | 0·12 |
| 0·15 | 191 | 164 | 152 | 0·12 | 0·15 |
| 0·2 | 247 | 204 | 184 | 0·15 | 0·2 |
| 0·25 | 295 | 244 | 214 | 0·2 | 0·25 |
| 0·3 | 351 | 283 | 240 | 0·2 | 0·25 |
| 0·4 | 452 | 357 | 288 | 0·25 | 0·3 |
| 0·5 | 534 | 422 | 332 | 0·3 | 0·4 |
| 0·6 | 641 | 499 | 384 | 0·4 | 0·5 |
| 0·75 | 774 | 604 | 461 | 0·5 | 0·6 |
| 1·0 | 1 036 | 803 | 595 | 0·6 | 0·75 |
| | | | *Paper cables.* | | |
| 0·0145 | 60 | 57 | 57 | 0·0145 | 0·0145 |
| 0·0225 | 79 | 75 | 75 | 0·0225 | 0·0225 |
| 0·04 | 113 | 105 | 104 | 0·04 | 0·04 |
| 0·06 | 151 | 138 | 135 | 0·06 | 0·06 |
| 0·075 | 180 | 162 | 157 | 0·075 | 0·075 |
| 0·1 | 225 | 199 | 191 | 0·1 | 0·1 |
| 0·12 | 252 | 220 | 210 | 0·1 | 0·12 |
| 0·15 | 303 | 261 | 246 | 0·12 | 0·15 |
| 0·2 | 376 | 320 | 296 | 0·15 | 0·2 |
| 0·25 | 453 | 377 | 343 | 0·2 | 0·25 |
| 0·3 | 523 | 435 | 385 | 0·25 | 0·3 |
| 0·4 | 663 | 543 | 464 | 0·3 | 0·4 |
| 0·5 | 804 | 648 | 540 | 0·4 | 0·5 |
| 0·6 | 960 | 767 | 624 | 0·4 | 0·5 |
| 0·75 | 1 180 | 930 | 738 | 0·5 | 0·6 |
| 1·0 | 1 548 | 1 211 | 932 | 0·6 | 0·75 |

The following examples will serve to show the effect on the rating factor of an uncertainty of this order in the evaluation of the thermal time-constant. Taking the formula for the calculation of the rating factor in the case already quoted (page 364), i.e. a cable which runs for 4 minutes at full load and 6 minutes at half load, it was found that if the thermal time-constant were taken as 1 300 seconds the "full" current could be increased to 1·304 times the normal current for continuous rating. If instead of 1 300 seconds the thermal time-constant were here taken as 1 200 seconds then the value obtained for the rating factor would be

$$n = 2\sqrt{\left[\frac{(1 - e^{-600/1\,200})}{4(1-e^{-240/1\,200}) + (1-e^{-360/1\,200})e^{-240/1\,200}}\right]}$$

$$= 2\sqrt{\left[\frac{0\cdot 3935}{(4 \times 0\cdot 1813) + (0\cdot 2593 \times 0\cdot 8187)}\right]} = 1\cdot 295$$

a difference of less than 1 per cent.

Take next the formula for the $\frac{1}{2}$-hour rating

$$n = \frac{1}{\sqrt{(1 - e^{-T/\gamma})}}$$

where $T$ the working period is $\frac{1}{2}$ hour (= 1 800 secs.).

If $\gamma = 1\,200$,

$$n = \frac{1}{\sqrt{(1 - e^{-1\,800/1\,200})}} = \frac{1}{\sqrt{(1 - 0\cdot 2231)}} = 1\cdot 134$$

But if we take $\gamma = 1\,300$

$$n = 1/\sqrt{(1 - e^{-1\,800/1\,300})} = 1/\sqrt{(1 - 0\cdot 2503)} = 1\cdot 155$$

a difference of 1·9 per cent for a variation of 8 per cent in the thermal time-constant.

Table 1 gives the time-constants and the direct multiplying factor both for $\frac{1}{2}$-hour and 1-hour rating for low-tension cables of sizes and dimensions as shown in the I.E.E. Wiring Rules, and Table 2 gives the actual permissible currents for this type of rating, and the sizes of cables which may be used for ratings of $\frac{1}{2}$ hour and 1 hour in place of the sizes at present specified in the Wiring Rules for continuous loading.

The thanks of the authors are due to Mr. S. Butterworth for his kindness in checking the mathematical portions of the work, and to Dr. Ezer Griffiths who determined the values of the heat capacity of the dielectric covering materials.

# AMERICAN PRACTICE AS REGARDS THE GENERATION OF SUITABLE VOLTAGES AND CURRENTS FOR DEEP THERAPY.*

By C. H. HOLBEACH, Associate Member.

(*Paper first received* 31*st March, and in final form* 6*th November*, 1922.)

### SUMMARY.

In the past few years considerable strides have been made in the improvement and simplification of X-ray equipment both for medical and industrial purposes. At the same time it is a noteworthy fact that the demands of X-ray workers are ever in advance of the apparatus at their disposal. It is for this reason that standardization is difficult, a design becoming almost obsolete as soon as perfection is approached.

The comparatively sudden call for highly penetrative X-radiations of shorter wave-length, involving the maintenance of 200 000 volts at the tube terminals for continuous running, has imposed many difficult problems on the designer and manufacturer. In America these difficulties were to a great extent solved by research laboratories of large electrical corporations. The influence of sound engineering principles is, therefore, more noticeable in American practice than in that of any other country.

### INTRODUCTION.

A certain ambiguity might be attached to the title of this paper, inasmuch as it presupposes the existence of a "practice" relative to the generation of high voltages for deep therapy in the United States. As only a short time has elapsed since medical authorities definitely called for shorter wave-length X-radiations, it might be argued that such an assumption is unduly hasty.

After careful consideration of the material and data available one might safely assert that a distinct practice exists. There is ample evidence of a fundamental similarity in equipment of apparatus placed at the disposal of American doctors for the treatment of deep-rooted malignancy. Such a condition of things, absent in the majority of other countries, is perhaps governed by circumstances peculiar to the United States.

In a general way one might perhaps suggest that the object of this paper is to point out some tentative lines along which a practice might be evolved in this country. There can be very little doubt of the ultimate benefit which would accrue from the standardization of electro-medical apparatus. At the present time there is a lamentable state of affairs which finds no parallel in other departments of electrical engineering. The medical man is faced with a host of conflicting recommendations which make his task an unnecessarily difficult one. There is no reason why a definite conclusion should not be arrived at, once and for all, to decide upon the basic principles which are to underlie the design of apparatus for deep therapy. Special refinements and secondary matters can be left to the discretion, enterprise and individuality of the manufacturer.

It is within the scope of this paper, therefore, to point out the steps taken by American manufacturers in perfecting their equipment, and it should be clearly understood that criticism will be excluded as far as possible, unless it is particularly required in order to emphasize some important point. Also, comparisons with similar efforts in this country will not be attempted, and indeed should be avoided, in view of the totally different conditions, both economic and otherwise, which, unfortunately, bind engineers in both countries.

### FUNDAMENTAL PRINCIPLES OF AMERICAN DESIGN.

The problems in the generation of high voltages for deep therapy are mainly centred upon:—

(1) The type and form of the high-voltage generator.
(2) The choice of X-ray tube to withstand 200 000 volts and over.

It is interesting to note that it is upon these more important general principles that, without exception, all manufacturers in the United States are in entire agreement. In order, therefore, to provide a means of generation of the higher order of potentials, recourse has been made to the a.c. oil-immersed transformer. The reasons are many, and certain external influences have, without doubt, had a measured bearing on this universally accepted principle. The presence, for instance, of alternating current in larger areas in the United States is in all probability a strong factor in this case. High-voltage electrical engineering has been applied to a far greater extent in America than in any other country. It is, therefore, scarcely surprising that manufacturers of X-ray apparatus should turn to a precedent which is already established in industrial circles. Transformers to operate on 200 000 volts were constructed some years ago in connection with high-voltage transmission lines in California and elsewhere.

Moreover, a transformer has been constructed having a secondary ratio up to 1 000 000 volts. An impression seems to be current in X-ray circles in this country that this apparatus was built by Dr. Coolidge for X-ray purposes. A correction is necessary, as the transformer in question was designed and assembled at the Pittsfield laboratories for the investigation of problems in connection with high-tension transmission lines.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

e.g. corona losses, lightning flash-over, and insulation tests.

But the main consideration regarding the adoption of a transformer in preference to a coil equipment is a purely electrical one, in the sense that engineers and research physicists have shown a marked preference for the former for continuous working with a minimum of attention.

The design of the X-ray transformer roughly coincides with its industrial prototype, inasmuch as without exception the core-type construction is used, with concentric windings and circular coils. In all instances the practice of oil immersion is followed for obvious electrical reasons. Experiments have been conducted at the Research Laboratory of the General Electric Co. at Schenectady, with a view to making a direct comparison of the X-ray intensities obtained from a Coolidge tube operated both on an induction coil and on an interrupterless transformer outfit. The measurements were made at 1 milliampere and 296 000 volts peak. The intensity was measured with various filter thicknesses of copper by means of a specially constructed ionization chamber. The results are given in the following table.

| Induction coil. 1 mA at 296 kV (max.) | | | Experimental interrupterless machine 1 mA at 296 kV (max.) | | |
|---|---|---|---|---|---|
| Thickness of copper | Time, $T$ | Intensity, $(1/T) \times 10^3$ | Thickness of copper | Time, $T$ | Intensity, $(1/T) \times 10^3$ |
| mm | secs. | | mm | secs. | |
| 0·1 | 9·1 | 109·9 | 0·1 | 9·1 | 110·0 |
| 0·2 | 10·8 | 90·0 | 0·2 | 11·3 | 88·6 |
| 0·3 | 12·9 | 77·5 | 0·3 | 13·2 | 75·8 |
| 0·5 | 15·7 | 63·8 | 0·5 | 16·9 | 59·2 |
| 0·7 | 18·2 | 55·0 | 0·7 | 18·1 | 55·3 |
| 1·0 | 22·2 | 45·1 | 1·0 | 22·6 | 44·3 |
| 1·5 | 29·6 | 33·8 | 1·5 | 29·3 | 34·1 |

The curve showing the relationship between intensity and filter thicknesses is shown in Fig. 1. It will be noted that all the points lie roughly on one line, and it is therefore obvious that any differences, both quantitative and qualitative, are such as may be assigned to experimental error. It is also evident that the virtues claimed for the induction coil are of no special value in relation to their operation with a hot-cathode tube, whereas, on the other hand, we have the manifold disadvantages of coil construction and the inconsistency in the running and upkeep of mercury interrupters.

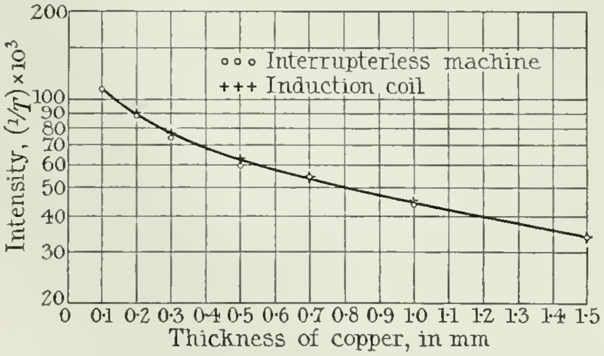


FIG. 1.—Absorption curves of interrupterless machine and induction coil; 296 kV (max.), 1 mA.

### HIGH-VOLTAGE TUBES.

The only type of tube employed by American manufacturers is the new high-voltage deep-therapy Coolidge tube, the outcome of five or six years of experience gained in experimental work. In fact, as long ago as 1915 a tube had been constructed by Dr. Coolidge to operate on 200 000 volts and over. The present tube (see Fig. 2) is of similar design to the well-known standard, universal-type tube, and consists of a solid tungsten anode supported by the usual molybdenum stem. The overall length has been increased to 32 in. and the bulb diameter to 8 in., and the distance between the cathode and anode has been carefully adjusted to comply with higher electrostatic strains consequent upon the increased tension. This correction minimizes the electrostatic pull on the filament, and also decreases the possibility of thermionic emission from the edges of the focusing cup. The new tube may be operated continuously at a current varying from 2 mA to 8 mA (depending entirely on the condition of the energizing supply and the methods of cooling employed). The factors limiting the energy input are governed by the volatilizing point of the tungsten anode and the melting point of glass. In the United States air-blast cooling is adopted but generally found to be unnecessary, as fully 8 mA can be passed without injury to the tube.

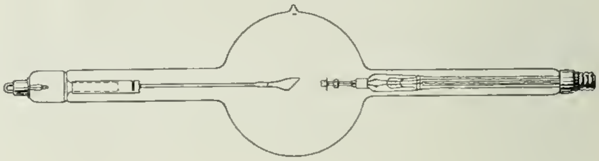


FIG. 2.

The current value employed determines to a great extent the ultimate life of the tube, which between 2 and 4 mA averages around 500 hours and over. Still higher currents decrease the life enormously until at 8 mA 40 hours would be considered a reasonable figure.

### RECTIFICATION.

The question of the supply of direct current to the tube has been solved by the universal method of cross-arm rectification, either of the " Snook " or the 2-arm pattern, of which the disc type is a modification. These methods are well known and need no description. The experimental apparatus used by Dr. Coolidge was equipped with a rectifying switch of the " Snook " pattern, and the shaft ($12\frac{1}{2}$ ft. long) was built up of paper-shellac tubing. The four metallic cross-arms were $35\frac{1}{4}$ in. long, spaced 33 in. apart. In this apparatus rectification up to 300 000 volts was obtained without difficulty.

Although the benefits of minimizing the corona discharge by the use of tubing instead of wire in the high-tension circuit, and carefully avoiding sharp corners, are well known, it is amazing how little this principle has been applied in this country. Its application in America has spread not only to the overhead system but also to the rectifier itself.

In Dr. Coolidge's apparatus the rotating collectors were shaped of 3-in. tubing, approximately 12 in. in length, and were fitted with hemispherical ends. The International X-ray Corporation of New York have gone a step further, and are responsible for an enterprising innovation in which the whole of the rectifying scheme involves the qualities of the sphere gap. It is claimed that by making all these collectors, both stationary and moving, of spheres and spherical toroids, a considerable number of inconsistencies in operation would be swept away. Fig. 3 shows the "Precision" rectifier mounted in position over an oil-immersed transformer. One of the outstanding advantages of the above arrangement lies in the fact that the whole system can be made more compact, and a greater latitude in the adjustment of the rectification can apparently be obtained, in view of the considerably shorter spark-over existent between spherical electrodes. The revolving toroids are within $\frac{1}{16}$ in. of the spheres, and during operation the arcing is claimed to be very small and to take the form of short local sparks, without the usual troublesome brush discharge attendant upon other forms of rectifier.

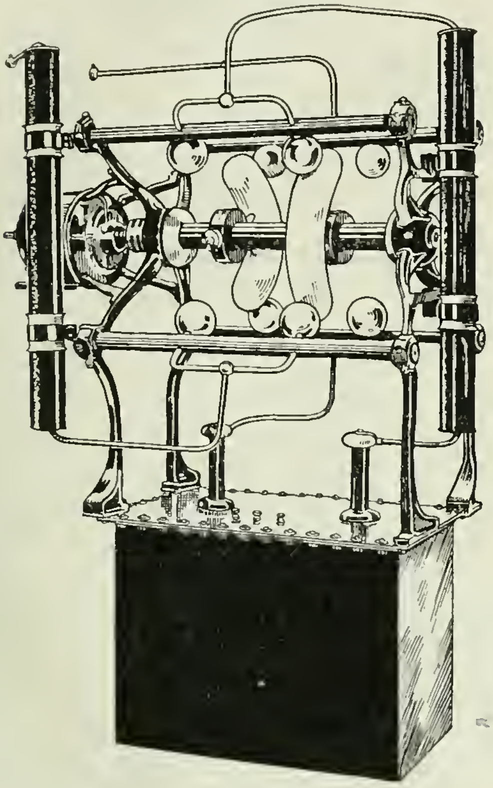


FIG. 3.

### CONSTANT-POTENTIAL APPARATUS.

Progress has been made with the methods of generating constant-potential direct currents involving the use of "Kenotron" valves. The system was first suggested and perfected by Dr. A. W. Hull of Schenectady for his work in connection with the X-ray spectrum examination of materials. The principles of the system depend, briefly, upon rectifying a high-voltage alternating current of 2 000 frequency by means of a battery of "Kenotron" hot-cathode valves. The pulsating direct current is then caused to charge up condensers of a predetermined capacity. The function of these capacities is to hold their charge until the next impulse occurs. This has the effect of flattening out the wave-shape, as shown in Fig. 4. In this manner a high potential is delivered to the X-ray tube, with a deviation of less than 1 per cent.

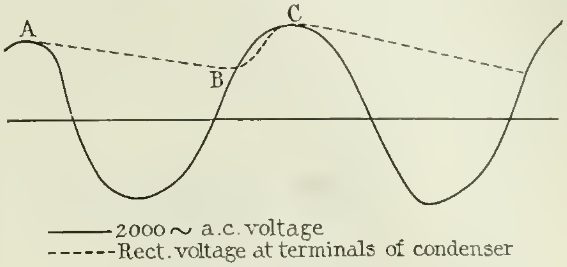


FIG. 4.

It is impossible to do full justice to this system in view of the many intricate factors which it would be necessary to discuss. Recently, however, an apparatus of this description has been designed and operated at a voltage of 200 000. The arrangement of connections is shown in Fig. 5. The supply to the primary of the transformer is obtained from a dynamometer-type generator giving 2 000 periods at 150 volts. The transformer itself sustains 100 000 volts at its secondary terminals, and is fed alternatively through the Kenotron valves $K_1$, $K_2$, $K_3$ and $K_4$, to the condensers $C_1$ and $C_2$. The tube is connected to the outer terminals of $C_1$ and $C_2$. A very fine adjustment of the secondary voltage is obtained by controlling the capacities of the condensers. In order to equalize the capacity currents, a small variable condenser is shunted across each valve. In this manner an even distribution of the voltage strains is obtained. At the present time no "Kenotron" valves have been constructed to operate at pressures above 150 kV, but no particular difficulty is anticipated in

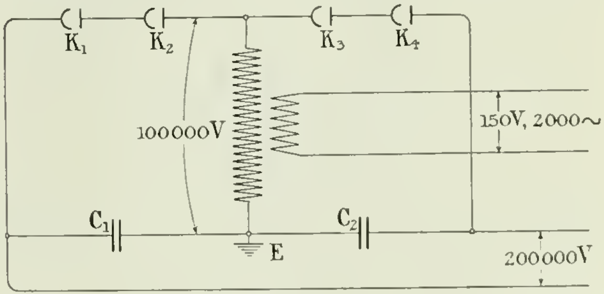


FIG. 5.

their development up to 200 000 volts if occasion demands. As soon as these higher power "Kenotron" valves are in use one valve may be substituted for the two, placed in each circuit as shown in the figure. The transformer is of very moderate dimensions, weighs only 85 lb. and has an open core. At the present time the transformer has been designed for 100 000 volts, but the voltage can readily be increased to 200 000 thus giving without any difficulty a constant potential of 300 000 volts at the terminals of a Coolidge tube. A comparison between the relative X-ray output of constant-potential apparatus, and of an a.c. transformer with mechanical rectifier, indicates a distinct margin in favour of the former. Fig. 6 shows this relationship clearly. To obtain the same X-ray intensity under identically similar conditions, 225 kV is required from an a.c. transformer outfit, as against 200 kV for the constant-potential apparatus. These comparative tests form a part of an extensive series of quantitative research problems which have been investigated by Dr. Coolidge and W. K. Kearsley at the Schenectady laboratory. The results have recently been published by *The American Journal of Roentgenology*. In summarizing the last-mentioned test Dr. Coolidge states that the difference might be due either to experimental inaccuracy or to the fact that the composition of the beam of X-rays is not exactly the same in both cases.

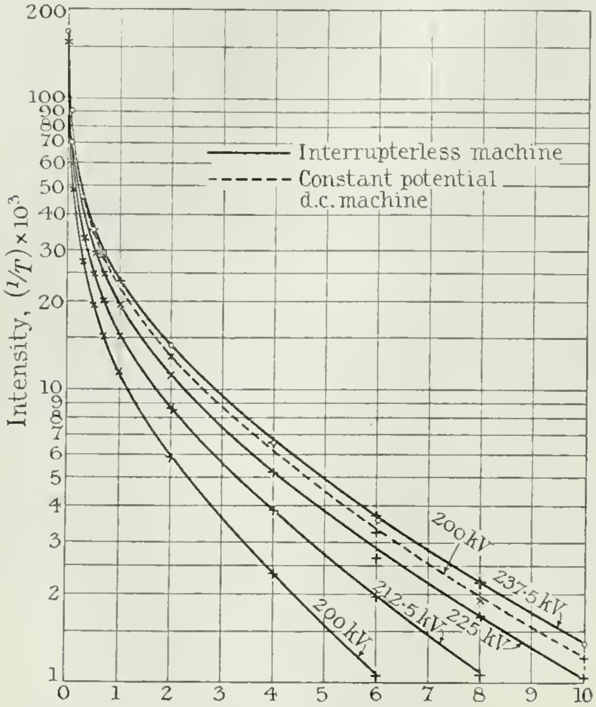


Fig. 6.—Absorption curves.

### Research.

Although research on this very important subject is not entirely confined to the "Victor" and the General Electric Co.'s combination, one necessarily feels that the most authoritative statements emanate from the Schenectady laboratories. Dr. Coolidge a year or so ago made a special journey to the Continent to study the question of deep-therapy equipment. Since then the research staff under his direction have had the opportunity of closely investigating the relative values of the most important types of German deep-therapy apparatus. Research of a very thorough and exhaustive nature has been carried out and recently published. In this way the benefits of unique experience are passed on to all concerned. The material outcome of this work is centred upon the deep-therapy outfit produced by the Victor X-ray Corporation at Chicago, a brief description of which will be given later in the paper. A summary of the already published research work would indicate the following conclusions :—

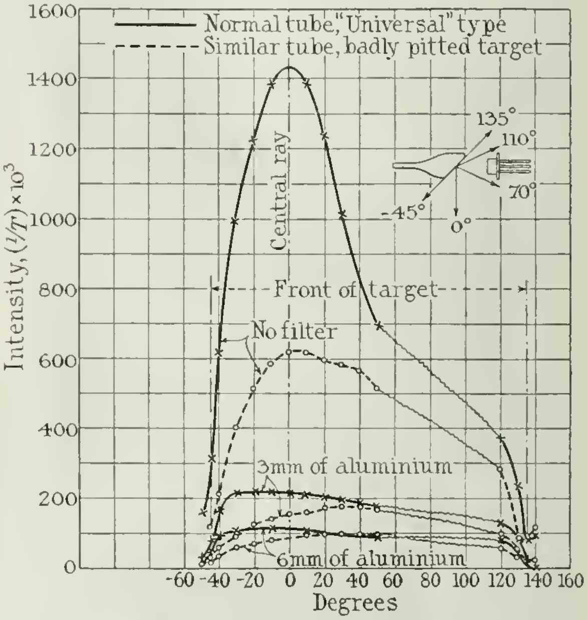


Fig. 7.—Distribution in plane containing tube axis and perpendicular to target face; 127 000-volt, 3-mA interrupterless machine.

(1) The oil-immersed a.c. transformer, in conjunction with a mechanical rectifier and the constant-potential machine, is the most efficient means of generating high voltages for continuous working.

(2) The present-day form of mechanical cross-arm type rectifier lends itself admirably, if suitably modified, to the rectification of higher potentials.

(3) The ballasting action of resistance offers certain well-defined advantages over auto-transformer control when operated with a hot-cathode tube at high potentials.

(4) A voltmeter connected across the primary of an a.c. transformer should be calibrated against a standard sphere gap.

(5) The current in the secondary or tube circuit must be kept virtually constant in order to minimize the high-tension voltage fluctuations due to the resistance in the primary circuit.

With regard to Coolidge tubes for deep therapy, experimental data are now available, the most important of which are as follows :—

(1) The 200 000-volt tubes have a substantially constant output. The filtered radiations through 2 mm of copper varied only $1\frac{1}{4}$ per cent over a series of 29 tubes, the terminal voltage being 200 kV at 2 mA.

(2) Where no filter is used for superficial skin therapy this constancy is lessened, owing to a slight variation in the thickness of the tube wall.

(3) The effect of the tungsten deposit on the inner walls of badly abused tubes may be neglected in deep therapy.

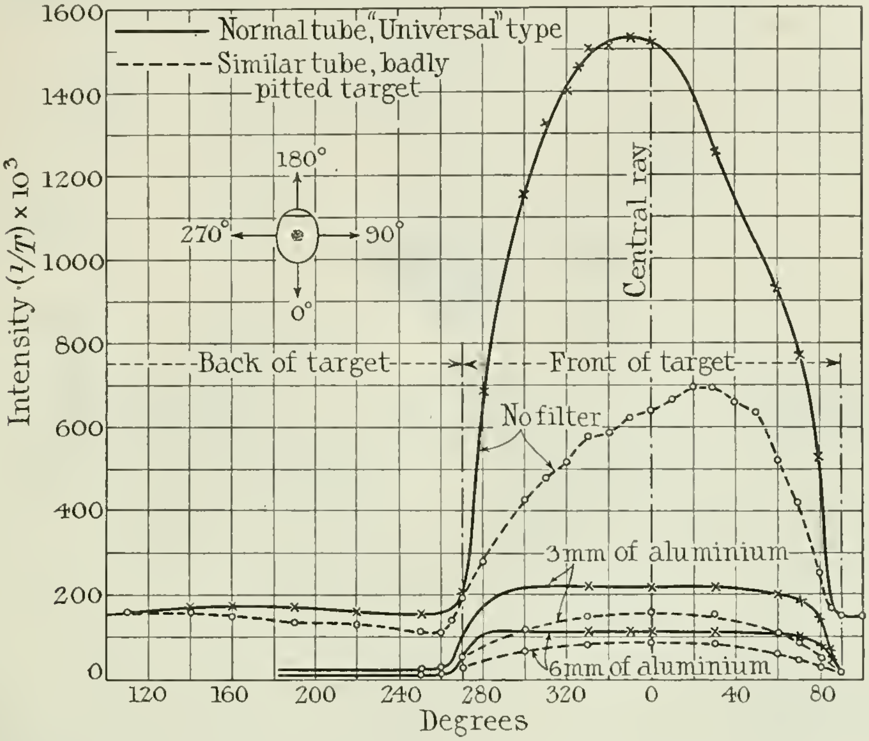


Fig. 8.—Distribution about girdle of tube ; 127 000-volt (max.), 3-mA interupterless machine.

(4) The distribution of intensity around the girdle, and in a plane containing the tube axis and perpendicular to the target face, varies markedly and, therefore, the angle at which the tube is operated is a factor of sufficient importance to warrant close attention. Figs. 7 and 8 illustrate the distribution in a quantitative manner.

The angles necessary for the application of X-rays through various ports of entry are in the latter case obtained by tilting a tubular or conical diaphragm placed in the path of, and radial to, the central beam. The radiations of varying incident angle are therefore directed on to the patient. It is obvious from the data already given that this technique must be carefully adjusted in order to allow for varying X-ray distribution from the focal spot. At the same time it should be noted that for filtered radiations the distribution is greatly flattened. Within the girdle of the tube the distribution is constant within angles of 100°.

These results are of the utmost importance in view of the fact that some workers in this country either have installed or are contemplating the installation of a tube carrier which is a fixture in relation to the patient.

### General Design of Apparatus.

Individual manufacturers in the United States have shown considerable enterprise in perfecting and modifying existent practice in order to cope with the new conditions. Many exceptional refinements have been applied to standard plants.

It was pointed out earlier in the paper that a similarity of design is noticeable. It would therefore be both superfluous and beyond the scope of this paper to give a detailed description of each piece of apparatus on the market, but it might be of interest to describe briefly some of the outstanding features of the more important American models.

A point worthy of note is that the twin-coil practice common in Germany has been followed in a modified form by some American manufacturers, and both the Waite and Bartlett Manufacturing Co. and the Wappler Electric Co. of New York have designed their transformer equipment in two halves. The latter company have two separate transformers energized in parallel, each being capable of transforming the line pressure to 150 000 volts. The transformers are oil-immersed and consist of concentric, heavily insulated, primary and secondary coils. Two tubes may be operated simultaneously, each taking alternate half-waves or, if desired, both halves can be applied unidirectionally to the tube. The diagram of connections is given in Fig. 9. Special importance is claimed for the inclusion of suitably designed ohmic resistances in the secondary circuit. Impressed surges and oscillations are minimized, the tube thereby safeguarded, and quite uniform running is maintained. The two rotating disc rectifiers are mounted centrally within the usual cabinet, over and above two oil-immersed high-tension transformers. Large ebonite shields are mounted at the stator to obviate the chances of flash-over to the earthed portion of the mountings, for instance the synchronous driving motor. The new high-voltage Coolidge tube is used and mounted in an ingenious protective container completely enclosed in such a way as to allow a draught of cold air projected by a fan to circulate around the tube bulb and out at the two arms. A sphere gap and coronaless overhead equipment is included in the installation.

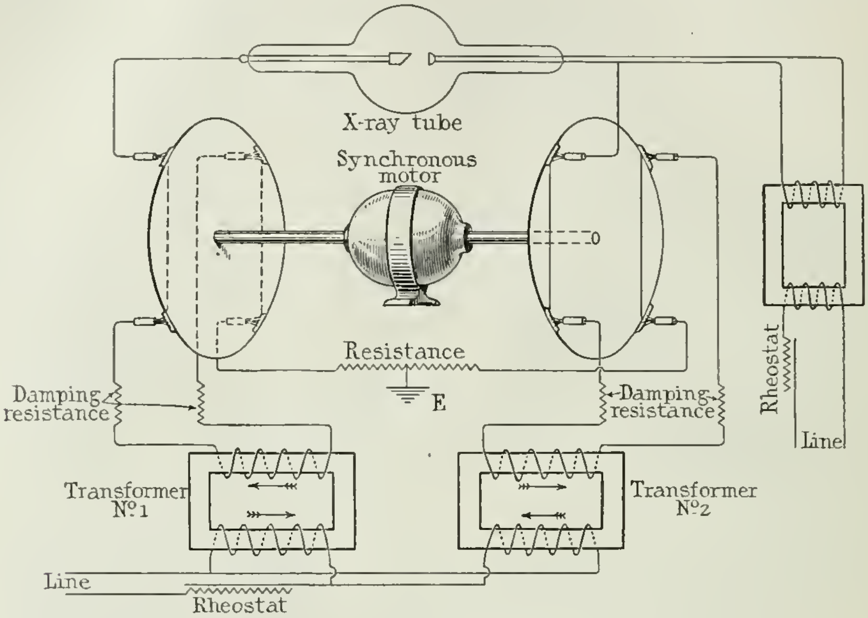


Fig. 9.—Diagram of connections of Wappler deep-therapy machine.

The Waite and Bartlett machine is somewhat of the same construction and has a single motor driving a shaft with a rectifier operating on the 4 cross-arm principle. The currents when rectified are put in series and fed to the tube terminals. A sphere gap and a primary a.c. voltmeter are included for measuring and standardizing the voltage. A machine of this type has been installed at the General Memorial Hospital under the direction of Professor Shearer, of Cornell University, who has devised a special recording instrument by means of which an ink record is taken of fluctuations (if any) in the primary voltage, the secondary current, time, and filter thickness. Dr. Waite attributes the utmost importance to this device, which eliminates carelessness on the part of the operator and, moreover, provides a permanent record of each treatment.

Mention has already been made of the rectifying system evolved by the International X-ray Co. of New York. Another interesting feature of the outfit consists of a new method of measuring the secondary voltage or penetration. This is done by detecting and calibrating the capacity current of a specially designed, concentric, air-dielectric condenser. The latter is mounted on the top of a cabinet, and a galvanometer or milliammeter is employed to record the capacity or corona current between the plates, the readings being directly calibrated in peak volts. The general appearance of the X-ray transformer and rectifier apparatus has already been illustrated in Fig. 3. The device is mounted on the top of the cabinet, and consists of a condenser, the discharge between the plates of which is measured through a galvanometer or milliammeter calibrated directly in peak volts.

It is claimed that by this means the errors due to the unskilled manipulation of a sphere gap are eliminated. Controls are obtained by a ballast resistance in the primary circuit of an oil-immersed transformer.

The actual design of transformer presents some interesting features. The secondary coils are completely suspended in oil, and no solid insulation or filling compound is used. The high-tension turns are made up of specially insulated wire capable of withstanding 5 000 volts (between turns). The transformer was designed by Mr. Montford Morrison and has proved to be exceptionally free from breakdown.

A powerful apparatus is manufactured by the Victor X-ray Corporation of Chicago, and is the practical outcome of the experience of their engineers in collaboration with the research work of Dr. Coolidge and his staff at the General Electric laboratories, Schenectady. Essentially the plant consists of a transformer capable of operating continuously at 280 000 volts, equivalent to a 20-in. gap between points. Rectification is obtained by the well-known Snook pattern cross-arm rotating switch. Special provision has been made to eliminate harmful surges. The apparatus has been designed with a view to its use on a still higher peak voltage than has so far been considered necessary for deep-therapy treatment. For this reason a greater latitude is allowed in the dimensions of the rotating switch, which is 5 to 6 ft. long and occupies the whole length of the cabinet. The cabinet, as usual, encloses the transformer and rectifying switch. The rotary switch is placed horizontally the whole length inside the cabinet. Noteworthy features of the apparatus are the inclusion of a Kearsley stabilizer, double-check milliammeters, and a conveniently placed sphere-gap voltmeter. The current stabilizer operating on the same principle as the Tirrill regulator is all-important, as it keeps the current virtually constant, even if considerable fluctuations occur in the line voltages. The results of the researches at Schenectady have proved the advisability of introducing two milliammeters in the tube circuit. It was found that surges which, although minimized, are unavoidable have been known to cause a partial short-circuit in the shunted resistance across the moving coil. A carefully calibrated meter of standard type was found to have failed in this manner after a very short period of use, and it was considered extremely improbable that two meters should fail in a similar manner at the same time. The voltages are measured by a voltmeter placed in the primary circuit of the transformer and calibrated against the sphere gap. Special attention has been given to the overhead system, which is made up of $\frac{3}{4}$-in. tubing and is so designed as to obviate all corona and attendant dangers. The output of the machine is as high as 8 mA at 200 kV and has an equivalence of 50 mg of radium. As many as 45 of these outfits are in use and are giving very satisfactory and consistent results.

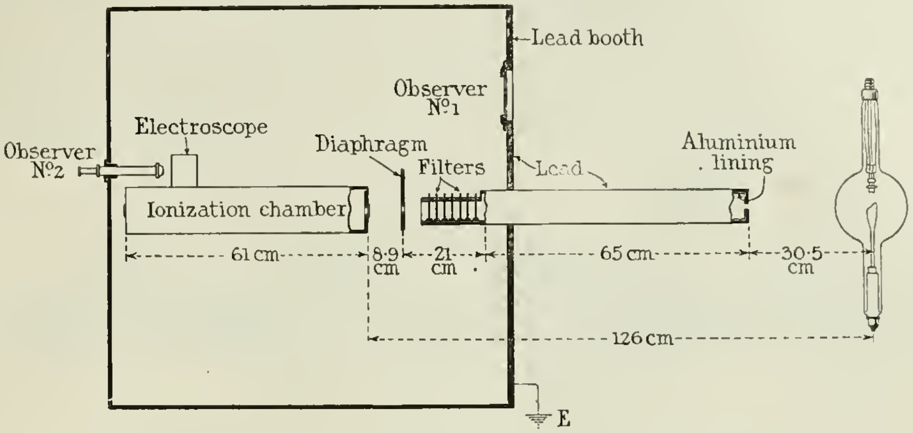


FIG. 10.

FUTURE DEVELOPMENTS.

It would appear that the limiting factors at the present time rest with the X-ray tube, and hence future developments depend entirely on the production of higher-power Coolidge tubes before apparatus for the generation of still shorter wave-lengths can be manufactured.

With regard to the question of standardizing methods of measurement for X-radiation, it appears that authorities in the United States do not recommend the use of an ionization chamber in everyday work. In the laboratory, of course, this method is pre-eminent, but, owing to the many disturbing factors requiring highly skilled manipulation, average accuracy could better be obtained by the use of a sphere gap checked by a primary a.c. voltmeter and double-check milliammeters. Still further accuracy would be obtained by the inclusion of some form of current stabilizer in the tube circuit. Differences in wave-shape may be neglected, as the quality and intensity of X-rays produced thereby are little altered, if the radiation is standardized in the first place for the maximum peak voltage.

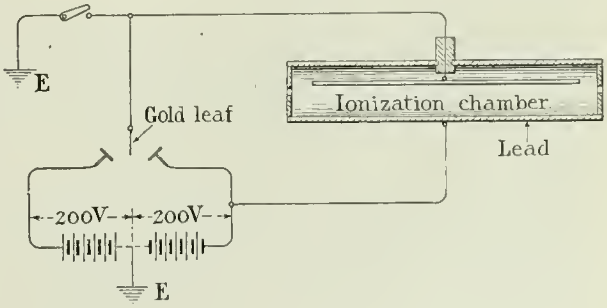


FIG. 11.

All sphere-gap measurements are performed in accordance with the recommendations and specifications issued by the Bureau of Standards of the American

Institute of Electrical Engineers, a very well-considered publication which is always a point of reference with regard to the measurement of the higher order of voltages.

Measurements in the laboratory by Dr. Coolidge were accomplished by means of the ionization apparatus shown in Fig. 10. The chamber itself is enclosed within a lead booth $\frac{1}{4}$ in. in thickness facing the tube, and $\frac{3}{16}$ in. elsewhere. It is found necessary, in order to protect the chamber from X-rays, to keep the door at the back closed throughout the measurement.

Fig. 11 illustrates the detailed arrangement of an ionization chamber connected with a dry battery and Bumstead electroscope.

In conclusion, the author would like to acknowledge the assistance and courtesy accorded to him by X-ray manufacturers in the United States. Also, special acknowledgment is due to Dr. W. D. Coolidge of the General Electric Co. Research Laboratory of Schenectady and to Dr. H. M. Imboden, the editor of *The American Journal of Roentgenology*, for permission to use the extract of Dr. Coolidge's paper before publication.

---

# AN APPARATUS FOR DEMONSTRATING THE MAGNETOMOTIVE FORCES PRODUCED BY SINGLE-PHASE AND POLYPHASE WINDINGS.[*]

By R. D. ARCHIBALD, Member.

(*Paper first received* 21*st July, and in final form* 16*th November*, 1922.)

## SUMMARY.

A description is given of a simple method of showing the variation in the M.M.F. of a single-phase alternator winding by the shadow of a vane attached to a rotating spindle.

The application of the same principle to the case of polyphase windings, and the method of arriving at the position and dimensions of the vanes, are explained.

An apparatus is described which is arranged to show the M.M.F. produced in the air-gap of an induction motor by the stator and rotor windings under load conditions, with the rotor either stalled or revolving.

The apparatus described was devised some years ago by the author for the purpose of demonstrating the rotating fields of induction motors and other a.c. machines. Since then it has been improved upon, and it is thought that a description of it might be of interest.

The principle on which it depends can be readily understood from the case of a single-phase winding with one slot per pole per phase (see Fig. 1). If the currents in the windings vary according to a sine law, the amplitude, *a*, of the M.M.F. curve varies in simple harmonic motion from a positive to a negative maximum. These variations can be shown on a screen by the shadows of vanes attached to a spindle rotated at a uniform speed, the beam of light being parallel and directed at right angles to the spindle, as shown in Fig. 2. The radial lengths of the vanes are equal to the maximum value of the M.M.F. The width of the conductor has been neglected in Figs. 1 and 2, so that the M.M.F. curve is a rectangle. We shall continue for the present to neglect the spaces occupied by the conductors in the slots, as these can easily be taken into account later.

With several slots per pole per phase the M.M.F. curve is stepped as shown in Fig. 3, in which there are three slots per pole per phase, and the vanes have to be shaped accordingly.

In the case of polyphase windings with one slot per pole per phase the vanes must have a width equal to the distance between the coil side of one phase and that of the adjacent phase. The radial length of the vanes must be equivalent to the maximum value of the resultant M.M.F. over the part of the armature periphery to which they correspond. The principle of construction is shown in Fig. 4 for the case of a two-phase winding. The vanes representing the M.M.F.'s of each phase are shown unshaded at I, I′ (corresponding to phase I) and at II, II′ (corresponding to phase II). The vanes representing the resultant M.M.F.'s at various positions round the armature periphery (or along the spindle) are shown shaded. They are the resultants of the unshaded vanes at any point along the spindle and are used for projecting the M.M.F. curve produced by the two phases. The unshaded vanes are, of course omitted, being mentioned here only for the sake of explanation.

The exact dimensions and positions of the resultant vanes may be determined as follows :—

Let *a* be the maximum M.M.F. produced by each phase—i.e. the radial length of an unshaded vane. Consider the first shaded vane at the left-hand end of the spindle. It is the resultant of vanes I and II′ at right angles to one another and it will therefore have a radial length of $a\sqrt{2}$, and be at an angle of 45° to I and II′. If we measure the angular position of the vanes around the spindle in an anti-clockwise direction starting from the position of vane I, the angular position of the resultant vane can be defined as $-45$. This is a time angle. Distances along the spindle represent space angles or electrical degrees of armature periphery. The width of the vane expressed as a space angle is 90 electrical degrees. The positions, widths and radial lengths of the vanes can be tabulated as shown in Table I.

---

[*] The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

If there are several slots per pole per phase the M.M.F. changes at each slot, and separate vanes are required for each pair of adjacent slots, i.e. there are as many vanes as there are teeth.

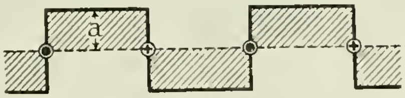


FIG 1.

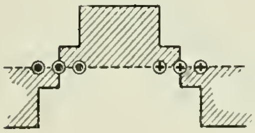


FIG. 3.

In order to show how the positions and dimensions of the vanes for a polyphase winding with several slots per pole per phase may be worked out on the above lines, an example of a three-phase winding with three slots per pole per phase is given in Fig. 5. The M.M.F.'s produced by each phase are shown at I I′, III III′, II II′. The current, and therefore the M.M.F. in phase III, is a maximum, so that the currents in phases I and II are half the maximum. The angular positions of the vanes which would project these M.M.F. curves are shown by the vectors to the right of the diagrams.

TABLE I.

| No. of vane (starting from left) | Radial length | Width, in electrical degrees | Angular position around spindle |
|---|---|---|---|
| I | $a\sqrt{2}$ | 0–90 | $-45$ |
| 2 | $a\sqrt{2}$ | 90–180 | 45 |
| 3 | $a\sqrt{2}$ | 180–270 | 135 |
| 4 | $a\sqrt{2}$ | 270–360 | 225 |

The total M.M.F. due to all three phases is plotted in Fig. 6. The vector diagrams below the total M.M.F. curve show how the radial lengths and positions of the resultant vanes are found from those due to each phase. For example, vane $a$ is the resultant of vanes I, II and III at the position marked $a$ on the total M.M.F. curve. Each vane has a width equal to a slot pitch (since the slot width is neglected), or 20 electrical degrees.

The horizontal and vertical components of the vanes of each phase and resultant vanes and their angular positions are given in Table 2.

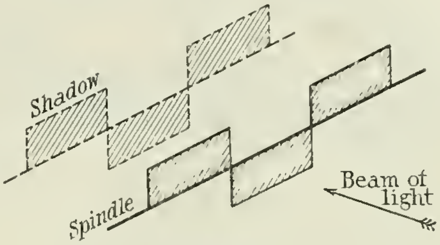


FIG. 2.

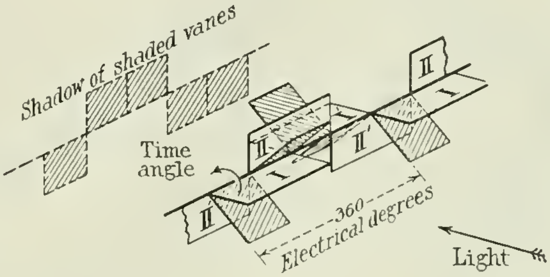


FIG. 4.

When the resultant vanes are mounted on the spindle over a space angle of 360 electrical degrees their projections in a direction parallel to the axis of the spindle appear as shown in Fig. 7. The ends of the projections of the vanes are on the hexagon (shown dotted). It is as important to have the projection of the vanes in an axial direction as it is to have it at right angles to the spindle, for the diagram so obtained gives a clear insight into the character of the winding. Each radial vector in Fig. 7 represents in phase and magnitude the M.M.F. opposite a tooth or space, with the corresponding letter in Fig. 5. The difference of M.M.F. between any one tooth and the next is caused by the ampere-conductors in the intervening slot; but the difference between any two M.M.F. vectors such as a and b (see Fig. 7) is the line joining a and b. Such lines as ab, bc, etc., therefore represent in phase and magnitude the ampere-conductors per slot between a and b, b and c, etc. These distances should all be equal in this case, since the number of conductors per slot and the maximum current in each is the same, and if the vanes have been properly calculated by the preceding method it will be found that the ends of the vectors in Fig. 7 divide the hexagon into two equal parts.

It will now be seen that we can arrive at the positions of the vanes more readily from this diagram than by the preceding method, by drawing the vectors of ampere-conductors per slot so that they are added together and form a closed polygon in 360 degrees. Radii are then drawn from the centre to the junctions of these vectors, thus giving the required positions of the vanes.

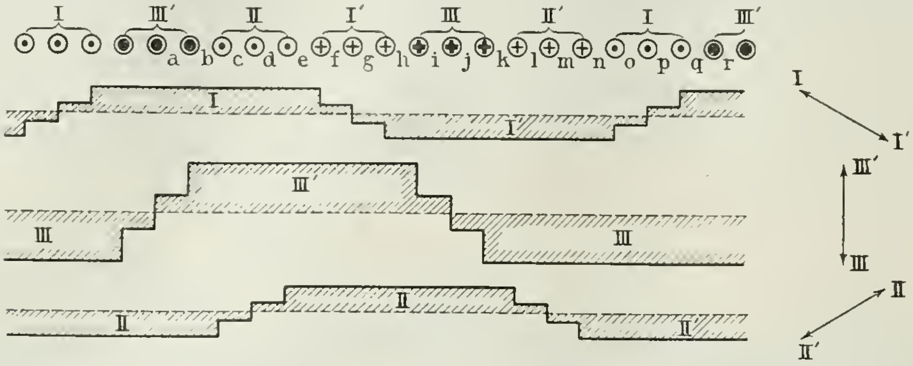


Fig. 5.

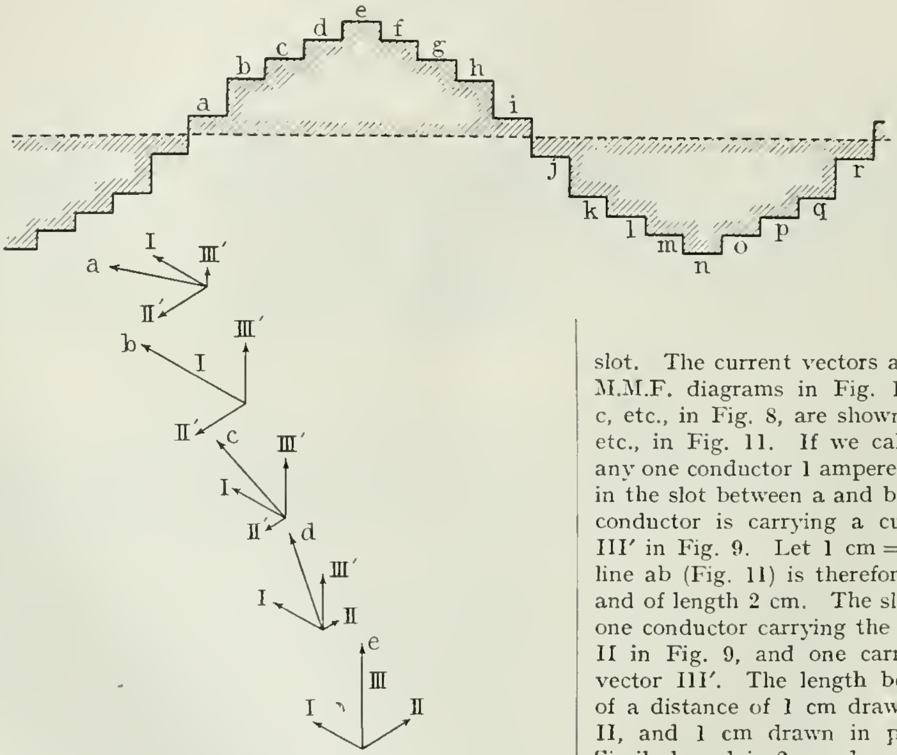


Fig. 6.

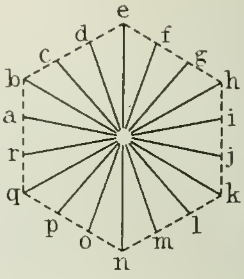


Fig. 7.

With symmetrical, full-pitch windings the figures bounding the vanes are simple, e.g. a hexagon for a three-phase winding, a square for a two-phase winding, and a $2n$-sided figure for $n$ phases. With short-corded windings the shapes of the figures are slightly modified and with variable-pole windings differ considerably from the simple forms. A number of M.M.F. diagrams constructed on this principle for such windings are given in an article by W. Stiel in the *Schweizerischer Elektrotechnischer Verein Bulletin* for January, 1922.

An example of this method of construction is given in Figs. 8, 9 and 10, which show a three-phase winding with three slots per pole per phase short-corded by one slot. The current vectors are shown in Fig. 9, and the M.M.F. diagrams in Fig. 11. The M.M.F.'s at a, b, c, etc., in Fig. 8, are shown by the vectors oa, ob, oc, etc., in Fig. 11. If we call the maximum current in any one conductor 1 ampere then the ampere-conductors in the slot between a and b (Fig. 8) are two, since each conductor is carrying a current given by the vector III′ in Fig. 9. Let 1 cm = 1 ampere-conductor. The line ab (Fig. 11) is therefore drawn vertically upwards and of length 2 cm. The slot between b and c contains one conductor carrying the current given by the vector II in Fig. 9, and one carrying current given by the vector III′. The length bc is therefore the resultant of a distance of 1 cm drawn in phase with the vector II, and 1 cm drawn in phase with the vector III′. Similarly, cd is 2 cm drawn in phase with the vector II, and so on.

In order to show the more correct trapezia form of M.M.F. curve it is only necessary to narrow down the vanes to the width of a tooth and join the outer corners of the adjacent vanes by a straight thread or wire. The outer edges of the vanes then trace out the M.M.F.'s over the teeth, and the threads or wires trace the M.M.F.'s over the slots. The idea will be gathered from Fig. 10, which shows three vanes connected in this way and the shadows produced thereby.

The apparatus so far described is suitable for demonstrating simple pulsating or rotating M.M.F.'s, such as occur in an induction motor on no load, but in a modified form it may be used to represent the resultant M.M.F. in the air-gap of an induction motor on load. Fig. 12 shows a stator winding having two slots per pole per phase and a rotor with three slots per pole per phase, both windings being full-pitch. The rotor is shown in such a position that the rotor phases are opposite the corresponding ones in the stator. The stator currents are given by the vector diagram in Fig. 13. Let the angle of lag in the primary circuit be 30° so that the E.M.F. $E_2$ in phase II is a maximum. The vector diagram of stator and rotor current, so far as phase II is concerned, will then be as in Fig. 14. From the primary current $I_2$ and the magnetizing current $I_m$ we find the rotor current $I'_2$, and hence draw the vector diagram of the rotor currents in each phase in Fig. 15. The radial diagrams for plotting the M.M.F. curves can now be constructed as in Figs. 16 and 17. Normally the M.M.F. of the rotor opposes that of the stator, but since we want to show the difference between the two curves, we invert one curve, say that of the rotor, and plot the curves as shown in Fig. 18. The resultant M.M.F. at any point is then given by the vertical distance between the two curves.

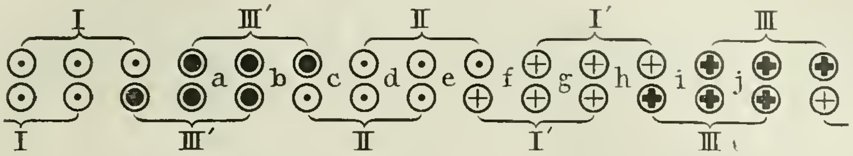


Fig. 8.

Table 2.

| Vane | Components of phase M.M.F.'s | | | | | | Resultant | | | Angular position |
|---|---|---|---|---|---|---|---|---|---|---|
| | Vertical | | | Horizontal | | | Components | | Radial length | |
| | I | II | III | I | II | III | Vertical | Horizontal | | |
| a | $\frac{1}{2}$ | $\frac{1}{3}$ | $-\frac{1}{2}$ | $-\frac{1}{2}\sqrt{3}$ | 0 | $-\frac{1}{2}\sqrt{3}$ | $\frac{1}{3}$ | $-\sqrt{3}$ | 1·76 | $\begin{cases}180^\circ\\ -10^\circ\ 54'\end{cases}$ |
| b | $\frac{1}{2}$ | 1 | $-\frac{1}{2}$ | $-\frac{1}{2}\sqrt{3}$ | 0 | $-\frac{1}{2}\sqrt{3}$ | 1 | $-\sqrt{3}$ | 2 | $\begin{cases}180^\circ\\ -30^\circ\end{cases}$ |
| c | $\frac{1}{2}$ | 1 | $-\frac{1}{6}$ | $-\frac{1}{2}\sqrt{3}$ | 0 | $-\frac{1}{6}\sqrt{3}$ | $1\frac{1}{3}$ | $-\frac{2}{3}\sqrt{3}$ | 1·76 | $\begin{cases}180^\circ\\ -49^\circ\ 6'\end{cases}$ |
| d | $\frac{1}{2}$ | 1 | $\frac{1}{6}$ | $-\frac{1}{2}\sqrt{3}$ | 0 | $\frac{1}{6}\sqrt{3}$ | $1\frac{2}{3}$ | $-\frac{1}{3}\sqrt{3}$ | 1·76 | $\begin{cases}180^\circ\\ -70^\circ\ 54'\end{cases}$ |
| e | $\frac{1}{2}$ | 1 | $\frac{1}{2}$ | $-\frac{1}{2}\sqrt{3}$ | 0 | $\frac{1}{2}\sqrt{3}$ | 2 | 0 | 2 | 90° |
| f | $\frac{1}{6}$ | 1 | $\frac{1}{2}$ | $-\frac{1}{6}\sqrt{3}$ | 0 | $\frac{1}{2}\sqrt{3}$ | $1\frac{2}{3}$ | $\frac{1}{3}\sqrt{3}$ | 1·76 | 70° 54′ |
| g | $-\frac{1}{6}$ | 1 | $\frac{1}{2}$ | $\frac{1}{6}\sqrt{3}$ | 0 | $\frac{1}{2}\sqrt{3}$ | $1\frac{1}{3}$ | $\frac{2}{3}\sqrt{3}$ | 1·76 | 49° 6′ |
| h | $-\frac{1}{2}$ | 1 | $\frac{1}{2}$ | $\frac{1}{2}\sqrt{3}$ | 0 | $\frac{1}{2}\sqrt{3}$ | 1 | $\sqrt{3}$ | 2 | 30° |
| i | $-\frac{1}{2}$ | $\frac{1}{3}$ | $\frac{1}{2}$ | $\frac{1}{2}\sqrt{3}$ | 0 | $\frac{1}{2}\sqrt{3}$ | $\frac{1}{3}$ | $\sqrt{3}$ | 1·76 | 10° 54′ |

Now consider that the radial diagrams in Figs. 16 and 17 are the axial projections of spindles carrying vanes. The shadows of these vanes cast by a beam of light in the direction across the spindles, shown by the arrow, would project the M.M.F. diagrams in Fig. 18 superimposed as shown. For this purpose the vanes must be transparent. In the device used by the author each vane is made of a couple of thin spokes with a thread or wire stretched across the ends, as in Fig. 19. In order to show the movement of the field with the rotor fixed, both spindles must be rotated uniformly at the same speed. Anti-clockwise rotation causes the field in this case to move to the right. In order to show

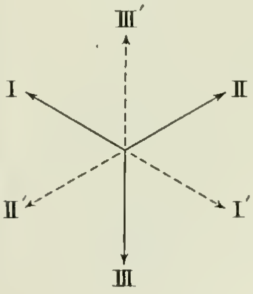


Fig. 9.

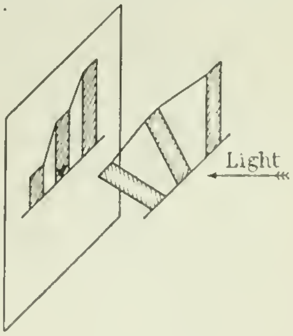


Fig. 10.

the movement with the rotor revolving it is necessary to move the spindle carrying the rotor vanes in an axial direction, i.e. into the paper in Fig. 17. Synchronous speed is shown by moving the spindle along without rotation in the direction of, and at the same speed as, the stator field. Slip is shown by moving the spindle at a speed greater or less than that of the stator field by the amount of the slip, and rotating the spindle at such a speed and in such a direction that the phase relationship between the stator and rotor field is maintained. Thus, if the slip were positive the spindle would have to be given a small anti-clockwise rotation.

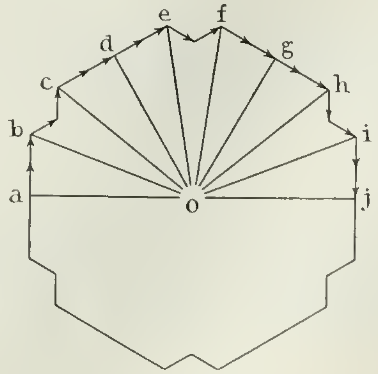


Fig. 11.

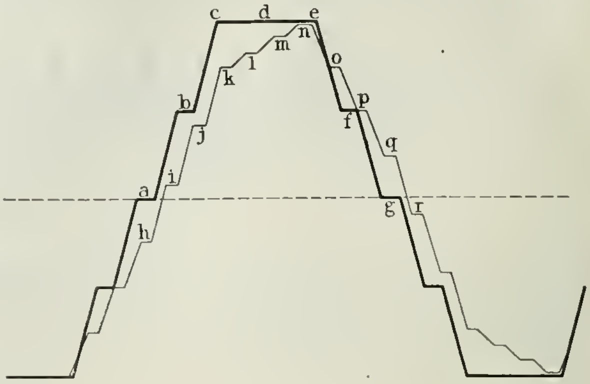


Fig. 18.

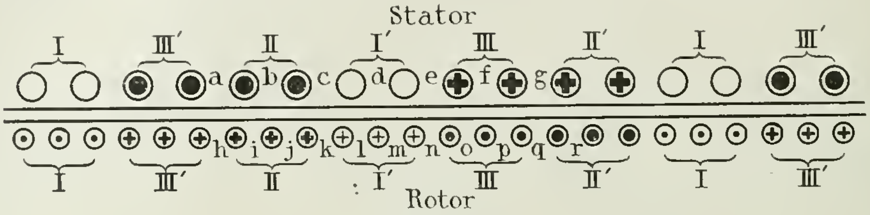


Fig. 12.

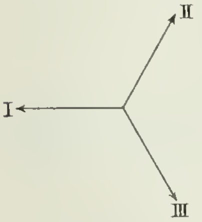


Fig. 13.

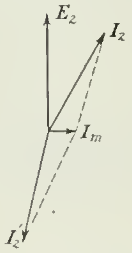


Fig. 14.

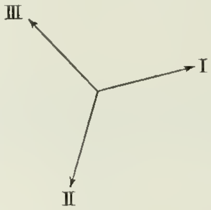


Fig. 15.

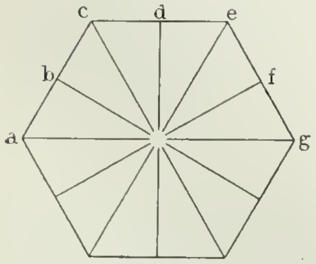


Fig. 16

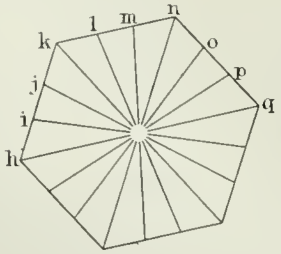


Fig. 17.

The device used to produce gliding alone, or gliding and rotation combined, is shown in Fig. 20. The spindle $s_1$ carries the stator vanes and $s_2$ the rotor vanes. On $s_1$ is fixed the pulley $p_1$ of diameter d. This pulley is detachable and can be replaced by others of different diameters. For showing synchronous speed d must be such that $\pi d$ equals the distance along the shaft which represents one cycle. To represent a slip of, say, 5 per cent, d would have to be 5 per cent smaller. A negative slip such as would occur in an induction generator would require d to be 5 per cent larger. A cord is attached to the shaft at a, carried along parallel to the shaft to the eyelet at b and thence round the pulley $p_1$, so that as $s_1$ rotates it draws $s_2$ along at the required speed. Rotation of the shaft $s_2$ is produced

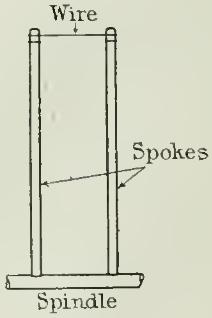


Fig. 19.

by the pulleys $p_2$ and $p_3$. The pulley $p_2$ revolves on the sleeve c attached to the carrier. The shaft $s_2$, which has a long feather, f, on it, passes through c and bears on the disc g attached to $p_2$. The disc has a key-way to fit the feather. The shaft can slide through $p_2$ in an axial direction whilst it is rotated by the pulley $p_3$ on $s_1$. The pulley $p_3$ is detachable and can be replaced by others of different dimensions for different slips.

To show the rotor stationary, $p_3$ must have the same diameter as $p_2$. For synchronous conditions the belt from $p_2$ to $p_3$ is removed and the pulley $p_2$ held stationary, as the shaft $s_2$ must not rotate. For a slip of, say, 5 per cent the pulley $p_3$ must have a diameter equal to 5 per cent of that of $p_2$.

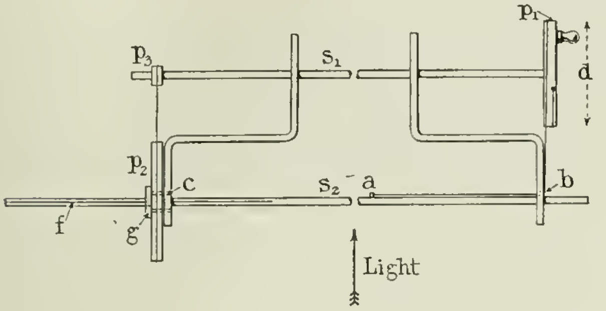


Fig. 20.

A useful addition to the apparatus is an arrangement to show the variation of the ampere-conductors per slot in the stator and rotor as the M.M.F.'s vary. This can be done by placing a drawing of the stator slots on the upper part of the screen and showing the variation of current by means of the shadows of vanes on a spindle rotating at the same speed as $s_1$. Each vane is opposite a slot and of radial length proportional to the maximum ampere-conductors per slot. For the rotor the spindle carrying the vanes is arranged for axial motion and rotation in the same manner as $s_2$, and a drawing of the rotor slots is placed on a slide which is drawn along at the same speed as the spindle $s_2$.

Very often only a simple demonstration is required, without the complication of the teeth. For example, the M.M.F. curve of a creeping three-phase full-pitch winding such as is shown in Fig. 21 can readily be shown by placing a number of spokes along the spindle at equal distances apart and spaced at angles of 60° round the spindle so that their projections along the spindle are radii to the corners of a hexagon. The ends of these spokes are then joined by straight, stretched pieces of wire or thread.

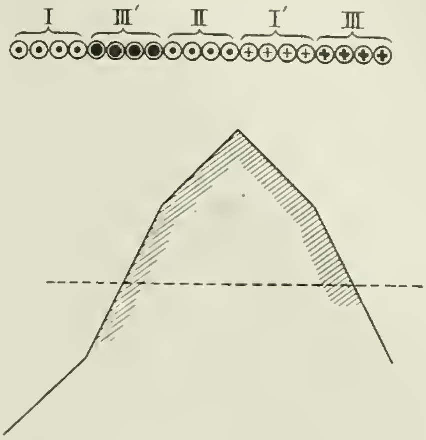


Fig. 21.

# DISCUSSION ON

# "THE POSSIBILITIES OF TRANSMISSION BY UNDERGROUND CABLES AT 100 000/150 000 VOLTS." *

SCOTTISH CENTRE, AT GLASGOW, 12 DECEMBER, 1922.

**Mr. A. E. McColl:** Jona, at the International Electrical Congress in 1904, described a rubber paper-graded cable, which was built by Messrs. Pirelli of Milan. This cable had, I believe, four gradings, and was designed for a working pressure of 75 000 volts. By interposing insulating material of varying specific inductive capacity in layers, a high electric strength is obtained. The choice of suitable materials is, however, rather limited, and the strengthening of the cable on this principle is not a commercial proposition, owing to the price of the materials available. Mr. Beaver † in 1915 put proposals before us for an intersheathed cable, and this certainly looked more promising than the original proposals of Jona and Russell. One difficulty in the intersheath method appears to be that the intersheath, being comparatively light, runs the risk of fusing or overheating due to the passage of large capacity currents on long lengths of cable. Further, it seems to me that any attempt to anchor the potential on the intersheath scheme will necessitate, on long cables, either resistances or transformers of large kVA capacity to absorb the energy in the capacity current. The author's cable seems to be an advance on the previous intersheath type, in that the intersheath is now employed to carry actual load current and the dimensions for the same maximum stresses are reduced. We can raise the pressures by employing single-core cable, but a certain loss is entailed, due to the sheath. The continuity of the sheath may be interrupted at frequent intervals, in order to suppress the secondary current which naturally tends to flow. With large currents, however, and increased spacings between conductors, considerable potentials may be obtained on the open-circuited sheath. The safer method, therefore, seems to be to incur the loss caused by short-circuiting the sheath at regular intervals. In this connection I should like to have the author's estimate of the increased loss in his cable due to the short-circuited sheath. I do not think that the author is correct in assuming that the capacity of the cable can be increased by releasing it of the charging current, as this relief would apply only to the supply end, the receiving end still requiring to transmit the wattless current between the capacity of the cable and the inductive load at the remote end. One of the most interesting parts of the paper is the comparison between 30 000-volt and 100 000-volt transmission. I do not think that the comparison is altogether fair, as a less expensive scheme could be made out for the 30 000-volt transmission. £1 000 000 is a large sum to spend on the transmission of 50 000 kW a distance of 30 miles, and in this country, where water power does not count, a separate station would in all probability be the better proposition if the conditions are such as to preclude the possibility of overhead lines. The use of cable such as the author has described is more likely to be of value in linking up an overhead line where intermediate stretches are, on account of local conditions, prevented from continuing overhead.

**Professor G. W. O. Howe:** The fundamental idea of the proposed system is a very sound one. It is well known that the weak point of high-voltage cables is the fact that the inner layers are stressed very much more than the outer layers. I am not very clear about the author's object in the first three or four pages of the paper, in which well-known results are apparently reached by a roundabout and approximate method, whereas the results can be obtained accurately with much less trouble. The author mentioned that, knowing the loss in the lead sheath and also its resistance, the current in the lead sheath could be calculated. It seems to me, however, to be a complicated calculation, since, after finding the loss in the lead sheath, one requires to know the distribution of the current in the lead sheath before that current can be calculated. The distribution of the current over the section of the sheath is by no means a simple thing to determine. I do not know whether the statement occurs in the paper but it was made by the author when expounding the paper. He made rather a strong point of the heating at that part of the cable which is nearest the conductor. Has it occurred to him that, instead of winding concentric conductors round a large central core, he might wind them round a lead water-pipe and pass water through the pipe? I am afraid that this will not impress the mains engineer as being a happy idea, but I do not know that it is any more fearsome than some other proposals in the paper, and I do not know that the mains engineer would be very much more worried with the water-pipe than in making and maintaining the 100 000-volt cable joints. There are one or two details of nomenclature to which I should like to call the author's attention. On page 222 the capacity of air is given per cubic cm, as if it were a function of the volume, instead of per cm cube; while on page 223 the author uses the term "specific resistivity." The resistivity is the specific resistance. On page 222 the author starts from the logarithmic formula and proves that the current is *approximately* constant; now as a matter of fact the logarithmic formula is based on the assumption that the current is the same throughout the dielectric. In Fig. 3 $R = 22$ cm and $r = 0 \cdot 65$; $R/r = 34$, therefore the capacities of two thin layers of the dielectric, one on the outside and the other on the inside, will be in this ratio and, the current being the same, the voltages must be inversely proportional. Assuming a constant power factor, the heat developed per cubic cm will be

---

* Paper by Mr. A. M. Taylor (see page 220).

† *Journal I.E.E.*, 1915, vol. 53, p. 57.

$34^2 = 1\,150$ times as great at the inner as at the outer surface. This reasoning is much simpler than the method followed in the paper, by which the ratio of 800 is obtained by taking ½ cm layers.

**Mr. A. F. Stevenson:** When Mr. Beaver read his paper in 1915, I asked for evidence of paper insulation having broken down, due to the inner layers being too highly stressed. We are still waiting for it. I think that it is more economical to use the ordinary strand than the hemp-cored, and thicken the insulation to give the same overall diameter. According to our present knowledge, six single cables would be more economical than two triple concentric cables for 100 000-volt transmission.

**Mr. D. Berry:** In the slides shown by the author there was an example of a single cable with a hempen core. It occurs to me that should a fault develop and moisture get in, this cable would break down. I understand that there has been some trouble in connection with the French cables, this trouble being attributed to mechanical damage. Our experience on a voltage of 20 000 with single cables has been that mechanical damage is not unlikely; the cable is so flexible that it is easily damaged, and sufficient care is not always exercised in the bending or handling. This is one objection to the use of single cables for high voltages. For voltages below 50 000 I do not suppose that methods other than those adopted at present are required, and I understand that a 50 000-volt three-core cable has been laid and is operating successfully. While I do not think that transmission by underground cables at 100 000/150 000 volts is of immediate moment, the matter raised by the author is of great interest, and I should be glad if he would give further particulars in regard to the insulation which he proposes that the cable makers should adopt for his cable. I should also be glad if he would indicate what we might expect in the case of a number of cables laid in a nest of ducts. It may be that in coming away from a station the cables are laid for some distance in ducts, and it is therefore to be expected that a great amount of heat will arise when the ducts are fully occupied. The cumulative effect due to the interaction of temperature and dielectric losses on the heating of the cables may be a vital factor at the high voltage proposed, and I should like the author's assurance that perfect safety, at any rate, can be looked for from, say, a number of cables of his design laid in the duct line for a certain distance.

**Mr. A. P. Robertson:** Fig. 13 shows the method of finishing-off the end of the cable so as to reduce the potential gradients at the approach to a joint, and it is stated that this is performed at the makers' works. It is not always possible to know exactly the length of a cable and where the joint will be. It looks rather a difficult joint. If a cable had to be cut, could the special insulation be put on in place? Fig. 11 is very complicated. The connections on a rotary converter are usually considered to be complicated, but as they are all in one station and close to each other it is a comparatively simple matter to check them; but in the case under consideration there are some 30 miles between the different sets of connections and, apart from the cost of these transformers and the space taken up by them, the risk of making a wrong connection seems to me to be very great. If it were only to be done twice, i.e. at each end of the cable, it is possible that no mistake would be made, but the author mentioned that on the route there may be tappings taken to substations. Would all these connections have to be made again at every substation? If so, the system would be very complicated.

**Mr. C. W. Marshall:** Practically the whole of the paper is devoted to the discussion of the question of dielectric stresses in the cables of the author's transmission system, and the actual question of power transmission is dealt with only in the most superficial manner. I am of the opinion that this point should have been thoroughly discussed before the question of dielectric stresses was touched on at all. It may be quite obvious to the author that the six-phase system which he advocates is workable, but he has been unable to convince me that it is so, either in the paper or in his exposition of it at this Centre. If, however, it is granted that the system of power transmission is practicable, I do not think that the objections raised by the *Electrician*—that the protection of the system would be almost impossible—hold, as this could readily be done on the low-tension side of the step-up transformers. From my own standpoint I feel that the paper is in a form which is wholly unintelligible to the majority of the members.

**Mr. A. M. Taylor** (*in reply*): In reply to Mr. McColl, I may say that I fully appreciated the difficulty of the risk of fusing or overheating the intersheaths during the passage of large capacity currents, owing to a breakdown at any point of the cable. There is no difficulty with these capacity currents in normal working, but it is admitted that during a breakdown they may be large. This difficulty is, however, sufficiently guarded against, partly by the copper section having to be sufficient to carry the ordinary load current, and more particularly by the arrangement shown in Fig. 12, whereby all the onus of transmitting large discharges of current, due to faults in the cable, is put upon the central core, which is of ample section and cannot be damaged by such currents. I do not quite appreciate Mr. McColl's point that "any attempt to anchor the potential on the intersheath scheme will necessitate, on long cables, either resistances or transformers of large kVA capacity to absorb the energy in the capacity current." If he refers to the conditions obtaining under normal working, I may say at once that, as far as I can see, all that is necessary is to have the six-phase transformers of sufficient capacity and sufficiently low reactance to maintain their voltage when passing the normal capacity currents. Under abnormal and breakdown conditions the discharges are, as I have already stated, taken care of by the central core, and in any case I fail to see how resistances would help the matter.

Mr. McColl's remarks in regard to the loss due to short-circuiting the lead sheath at regular intervals appear to be due to a misreading of the paper, because this is the only method considered therein, and the figures for loss given on page 221 are expressly for that condition. Mr. McColl further remarks that he does not think that the capacity of the cable can be increased by relieving it of the charging current. I think, however, that he has not fully considered Fig. 15, and I would suggest that the principle of subdivision between the different sectionalizations of the line can be continued to any extent desirable.

In reply to Mr. McColl's remark to the effect that a separate station would, in all probability, be the better proposition if the conditions are such as to preclude the possibility of overhead lines, I may say that, for the addition of another £80 000 or so outlay for copper, my scheme could be employed to transmit 100 000 kW, and that under these conditions I assume that the annual charge for interest and sinking fund on the cables for a 30-mile transmission will not exceed about 0·035d. per unit transmitted, i.e. about the cost of transmission of coal. If, however, as I anticipate from recent conversations with cable makers, it becomes possible to employ approximately 150 000 volts in transmission, then over the same cables it will be practicable to transmit 150 000 kW, and under these conditions the capital charge on the cables would be reduced to about 0·018d. per unit transmitted. This would be of the order of only 60 per cent of the charges for coal transmission. Conversely, the distance might be raised to 50 miles and even considerably more, if arrangements could be made for supplying the capacity current in the manner indicated in the paper. The foregoing figures are for a 40 per cent load factor and do not take account of the loss in transmission.

In reply to Prof. Howe, I gather from Clark and Shanklin's tests that the cross component of the current in the lead sheathing is of nothing like the same significance as the longitudinal component. No doubt the cross component becomes more important as the centres of the three cables more nearly approach one another. On the other hand, according to Mr. Dunsheath's tests, even where they approach one another very closely—as in his three-core cable—this effect is not so serious as to be prohibitive. In any case, the losses in Clark and Shanklin's cable " C "—upon which I have based my estimates for the losses in the cable shown in Fig. 1—were obtained by careful measurement and *include* the loss due to these cross currents.

With reference to Prof. Howe's remarks as to the 100 000-volt cable joints, I am assured by two, if not three, cable makers, that they do not anticipate any particular difficulty in this respect. Moreover, the joints in my scheme are not 100 000-volt joints; they merely consist of a succession of joints with 30 000 volts between each, and the outside joint has only 15 000/20 000 volts between it and the lead sheathing.

I would refer Mr. Stevenson to a paper read before the American Institute of Electrical Engineers by Messrs. Middleton, Davis and Davis, in which are numerous cases of cable lengths being broken down due to the stresses being too heavy.

In reply to Mr. Berry, who refers to mechanical damage arising from the cables being too flexible, I think he can hardly have realized that, in the present case, the cables will certainly not suffer from this fault, particularly if they are steel-wire sheathed. With regard to his suggestion that I should give further particulars of the insulation which I propose that the cable makers should adopt for my cable, I would say that this matter has been left with the cable makers, and I believe that impregnated paper, employing a mineral-oil base, is what they would recommend.

In connection with the heating of cables in ducts, I think that Mr. Berry has not appreciated that I am only considering trunk-line transmission along the main lines of railways, where not more than three cables would be together on each side of the railway. These cables would be, preferably, carried above ground and sheltered from the direct rays of the sun, and space would be allowed between them for the circulation of air. I think, also, that he has not appreciated that only six cables would be required to transmit 100 000 kW, and possibly 200 000 kW.

Mr. Robertson, in common with Mr. Berry, has not appreciated the fact that my cables are primarily intended for laying along the sides of a railway track, being carried a few inches above ground, where the position of a joint would be very readily adjustable. I do not see why a selection of cable lengths, all within a foot or two of one another, should not be supplied on different drums in cases where there is any likelihood of difficulty in finding suitable spots for the joints. As regards the final joints leading into the power house or the substation, it would not matter if these came in the ordinary part of the cable, because they would be jointed under exceptionally favourable conditions, and, being so few in number, very particular care could be given to them without undue expense being incurred.

In reply to Mr. Robertson's inquiry as to whether all the tappings would have to be made at every substation, I would suggest that the cables would be simply opened out at the substations and carried to suitable terminals or busbars, and though, of course, considerably greater care would be necessary than in the case of existing systems to see that all the connections were absolutely correct, yet this only occurs at the initial installation of the line, and is, I am sure, not beyond the capacity of many of our erecting engineers. The joint shown in Fig. 13 looks unnecessarily complicated, because at the time when that figure was prepared I was considering lead intersheaths under both the outer and intermediate cores.

I submit that the complications which Mr. Robertson sees in connection with Fig. 11 will disappear on better acquaintance with the scheme.

In reply to Mr. Marshall, I believe that a few words with me would lead him to withdraw the statement that he is not satisfied that the six-phase system is workable. I have found that in all cases where I have had an opportunity of discussing the matter in detail with any engineer, the difficulties at once disappear. If Mr. Marshall will communicate with me direct, I shall be very pleased to endeavour to take up with him any points which he may find difficulty in accepting. From my own point of view, I cannot see any practical difficulty in the matter of the transmission of the power. I have looked quite carefully into the question, both by myself and in conjunction with other engineers, and no slip in my deductions has yet been pointed out.

I regret if the point has been badly presented, but my reply to this must be that, having satisfied myself that the six-phase transmission was perfectly workable from the point of view of transmitting the power, it became of prime importance to demonstrate where I had effected real progress (in the voltage that might be employed), as otherwise my critics would have said that what I was bringing forward produced no effective result beyond what could be effected by ordinary methods with much less complication.

I submit, however, that if I have succeeded in trebling the voltage which can be obtained with ordinary methods, a small amount of complication in the initial connecting up will not militate against the scheme, in view of the advantages effected by such an increase in voltage.

## Mersey and North Wales (Liverpool) Centre, at Liverpool, 15 January, 1923.

**Mr. A. E. Malpas :** As regards the subject of underground cables to work at 150 000 volts, the usual limit of diameter for an armoured cable is 4 in., any greater value involving serious risk of cracked insulation. It is quite probable, therefore, that a cable with an intermediate lead sheath such as the author proposes, after having been rolled on and off the drum would contain incipient cracks which might not be noticeable under a pressure of, say, 45 000 volts, but which might easily lead to breakdown under the higher pressure, more particularly when the effect of surges is taken into account. I should like the author to say why he finds it necessary to introduce the intermediate lead sheathing below the outer conductor of the cable. It would almost appear that as the lead is at the same potential as the copper, the latter itself could have been used for the purpose in view and the lead sheathing suppressed. Assuming for the moment that the method suggested be feasible and that the estimate of cost given in Appendix E be correct (I have no means of checking the latter), then the cost of the capital charges at 7½ per cent is 0·55d. per kWh on a relatively short line of 30 miles. The cost of the installation amounts to 7s. 6d. per kW per mile, which seems a low figure. In his recent address * our Chairman quoted the case of a 250-mile transmission line in America on which the transmission charges, including capital and depreciation, amount to only 0·16d. per kWh, so that on this basis an undergound cable of equal length and voltage would increase the cost of power by 4·4d. per kWh, or nearly 30 times as much as in the case of transmission by overhead lines.

**Mr. W. Holttum :** The development of paper-insulated cables has led to the use of increasingly higher values of maximum stress in the dielectric, until it now appears that we are within sight of the limiting voltages of transmission by impregnated paper-insulated cables due to the limit of dielectric stress having been reached. In this paper we have an attempt to increase the possible voltage of transmission by other means. The author has shown very clearly in Section III the inherent disadvantages under which the dielectric of a cable works, owing to the concentration of stress and heat in the dielectric near the copper surface, and he attempts to overcome this by the use of intersheaths. The paper affords a very interesting object lesson of the kind of arrangement which results from such an attempt. Fig. 5 illustrates an application of the principle of intersheaths and clearly shows that, while some redistribution of stress is obtained, the current carried by the outer two cores is at a lower voltage than that in the centre core, i.e. the copper in the outer two cores is carrying less power per square inch of cross-section than that in the centre core. In the second paragraph of Section V the author states that by his system all the cores are utilized " equally for the passage of heavy load currents without seriously diminished voltage on each circuit." This seems to be a vital point in the whole scheme, and I contend that whatever is gained by the redistribution of voltage gradient in the dielectric must necessarily be counterbalanced by a lower effective working voltage of a portion of the copper, and any apparent gain is entirely illusory. The method of jointing in which the end of the cable is prepared in the factory as shown in Fig. 13 prevents any adjustment of joint positions in laying except by burying superfluous cable, and in some places this feature would be a serious inconvenience. The protection afforded by the extra sheath is apparently lost at joints, where penetration of the outer sheath would allow moisture to enter the middle of the cable. In addition, jointing would be difficult and costly. I should like to comment in detail on the conclusions* given in Section VII, and I suggest that on examination they do not show very much in favour of the system. The first four points emphasize reliability only. It may be argued that the reliability of ordinary three-phase cable transmission is satisfactory, and probably as great as that in the author's system, considering that several cables would have to be used to transmit sufficient power to justify its use, and that not more than one cable would be likely to break down at once, in which case one of the ordinary type could be replaced more simply than one of these special cables. Conclusion (5) applies in some measure to any three-phase cable, and on a 30-mile line very considerable power-factor improvement would be effected by the capacity of ordinary three-core cable. Conclusion (6), as already suggested, is compensated for by the reduced power transmitted per square inch of copper section of the outer cores. Conclusions (7) and (9) appear to require further explanation, and in any case are light-load advantages only ; the same advantages would appear to be gained in ordinary transmission with a number of cables by switching in only sufficient cables for the load. Conclusion (10) does not appear to offer any advantages over an ordinary system which would be extended to deal with a growing load by adding more cables. Conclusion (11) offers no advantage in view of the economy of three-core construction on the one hand, and on the other the fact that with 100 000-volt single-core cable the core would almost certainly be made solid with a view to making use of the whole copper section. Conclusion (12) is merely negative. This leaves only conclusion (8), which appears to be much more than counterbalanced by the three disadvantages stated in the paper. I would suggest that the system described in the paper would be more easily understood if Fig. 7 were given in greater detail showing exactly how the transformers are individually connected and how the three-phase supply is fed in.

---

* See page 31.

* Since superseded by others which will be found in the paper as printed in the *Journal*.

**Mr. T. D. Clothier** : Many of the diagrams and other matter in the paper bear evidence of evolutionary stages of what is presented as the main subject ; for instance, Fig. 13 illustrating the suggested cable end, apart from being a separate idea, shows two inner lead sheaths, three in all, there being no reference to these elsewhere. The purpose of other diagrams is hardly apparent, and those essential are insufficiently explained. There are apparently four transmission systems, three being similar and described as six-phase, but they seem to be really three-phase six-wire combinations at 60 000 volts across each separate phase, there being no interconnection at the middle position. Each of these similar parts is referred to in the paper as a " hexagon " and is repeated three times ; except as regards the selection of the common earthing point the author has made this reasonably clear. Here, however, I at least have been unable to decide where and how the fourth system referred to as the " major star " is connected in or superimposed upon the two inner conductors in each of the three systems. At first, Fig. 7 seemed to give a key to these transformer connections ; on examination, however, it appears that two single-phase supplies with a 30° difference of phase are separately produced from somewhere and superimposed on two " hexagons." I suppose that in the case of the three-phase combination all the circuits are in some way derived from one simple three-phase generated supply, and that all are again re-convertible. An ordinary diagram of connections would have been very much appreciated. The author only compares the cost for the proposed system with that of transmission by 10 cables at 30 000 volts, and no comparison is made with the cost of a straight 100 000-volt system with earthed neutral using 57 000-volt single-core cables, it being presumed probably that these cables cannot be manufactured. It is shown in the paper, however, that three sets of these cables, any two of which would be sufficient to transmit the power under consideration, would contain only 1·665 sq. in. of copper section against 2·532 sq. in. in the author's six cables, hence, if this type of cable can be made, it will no doubt summarily dispose of any application of the author's proposals. An attempt to reconstruct the system from the schedule of equipment was no more successful. A total of 42 transformers, of four sizes and ratios, with an aggregate capacity of 227 000 kVA as compared with 30 similar transformers of 126 000 kVA proposed for the 30 000-volt system, seems to require some further explanation. The diagram of the cable in Fig. 6 gives a misleading impression of a section of the cable, for the outer conductor is placed upon a lead sheath of over 3 in. diameter, but it has an area of only 0·08 sq. in. and consequently will be made up of rather fine strands ; the area, for instance, compares with 0·107 sq. in. for the intermediate conductor. Again, the finance (at the end of Section VI) based upon the estimated annual saving of £375 is certainly faulty, and as it is not essential to the merits of the main theme it seems regrettable to have introduced it. The essential proposition contained in the system seems to be to transmit one half of the power at 60 000 volts through 6 conductors, arranged in pairs of triple-concentric cables with a common neutral point in the centre of one phase, and to use the intermediate and outer conductors for the purpose of splitting the dielectric into thinner sheaths than would otherwise be necessary ; and at the same time to superimpose additional current upon the inner cores in order to transmit a similar amount of power at a pressure of 100 000 volts. The proposal seems to be quite feasible and an advance on previous suggestions to use intersheaths for this purpose, but its commercial application depends largely upon the possibility of producing reliable single-core cables capable of working at the same pressure without the intersheaths.

**Mr. A. B. Mallinson** : In his opening remarks the author speaks of having had offers from two or three cable makers to make and lay high-pressure cables which would be guaranteed for one year ; such a short period would be totally inadequate to secure consideration for a proposition. I entirely endorse the remarks made by Mr. Holttum about the method of finishing-off the ends of a cable, as shown in Fig. 13. One can imagine the hopeless position of the mains engineer who has to have the finished joint on the end of his main made at the makers' works. It is utterly impossible for anybody to give a definite length for a cable to be laid underground, as one may come across obstructions which mean diversion when the ground has been opened up. One has to assume, therefore, that there would be little loops to be accommodated at the ends, which would certainly not be advantageous. To my mind the important part of the paper centres on the conclusions given on page 232 ; if all the claims can be substantiated they certainly constitute very important and valuable advantages, but the disadvantages compared with a 30 000-volt three-core line are equally vital. I particularly notice that the induced currents in the lead sheathing are considerably increased where the cable centres cannot be kept within 6 or 7 inches. I cannot see how the author can get his cables so close, unless they are laid on top of each other, which would be unsatisfactory ; and further, even if this could be done, it would mean quite a large cross-section for the main as a whole, difficulties in underground laying being thereby increased.

**Mr. W. P. Fuller** : I think that the author has exaggerated the effects of temperature on cables. It does not seem clear whether the remarks in the paper and the curves shown on the lantern slides refer to d.c. or a.c. resistivity. The fact that the d.c. resistivity falls rapidly as the temperature rises is a matter of no great moment. If the curves refer to the a.c. resistivity they must refer to somewhat old cables. A modern high-voltage cable can be made to have a very nearly constant power factor, and less than 0·01 over the working range of temperature, and consequently the dielectric losses are very nearly independent of the temperature. With regard to intersheaths, it is a mistake to aim at obtaining a uniform stress, because the breakdown of a dielectric is not altogether a function of the maximum stress. It must be looked at in a different light from that of a metal structure failing under steady loading. In general, as the diameter of the conductor is increased the stress must be reduced if the factor of safety is to be preserved. It is unfortunate that in the author's intersheath cable the voltages are 60° out of phase. Had there been no intersheaths at all, 60 000 volts applied between core and lead would produce across the $\frac{1}{2}$ inch of dielectric next to the core a potential difference of 33 000 volts. As it is 30 000 volts with the intersheaths present, the gain from their use is negligible.

**Professor E. W. Marchant :** On page 222 is given the result of some calculations of the condenser current per foot of cable across different sections of the dielectric. The power factor of the dielectric has been assumed to be the same throughout, and under these conditions the capacity current must be the same across all sections. On page 223 the author refers to the increased dielectric loss in the inner sections of the dielectric of his cable. This result is, of course, very well known. The energy stored in a dielectric is proportional to the square of the dielectric stress and, therefore, if the power factor of the dielectric is constant it follows that the power loss due to dielectric hysteresis is proportional to the square of the dielectric stress. The method described of using intersheaths on the cable in order to reduce the maximum dielectric stress on the inner portion of the insulation is, of course, comparatively old. It is undoubtedly a great saving to diminish the dielectric stress in the inner layers of the cable. This may be done either by using material of greater specific inductive capacity or, as Mr. Beaver suggested, by using intersheaths. It seems very doubtful, however, whether it will be worth while to try to diminish the current which is carried by the intersheaths by introducing auto-transformers at different points along the cable to supply the necessary charging current. In this connection Mr. Torchio's statement quoted on page 228 may be aptly quoted, i.e. " The assuring of reliable operation is vastly more important than getting the maximum rating out of a certain mass of metals." With regard to the system itself, it is difficult to follow it completely from the paper. The closest analogy to it would seem to be a three-wire a.c. system with the centre point of each phase earthed (see Fig. E). The author proposes to use an earth on one side of his " hexagon " of which the other side is about 60 000 volts above earth, whilst the other pair of cables is about 60 000 volts below earth. In the arrangement which he describes, the potential difference between the inner conductor and the first intersheath conductor would appear to be 30 000 volts ; between the first intersheath conductor and the next one it will also be 30 000, and between the outer intersheath conductor and the sheath there is a further 17 800 volts, so that the total pressure, added numerically between the inner conductor and the sheath, is 77 800 volts. Of course the pressures between the conductors are not in phase with one another, but from the point of view of dielectric stress this is not of importance. If the cable were working as an ordinary 100 000-volt three-phase cable with the centre point of the phase earthed there would be a total difference of pressure between the phase and the earthed middle point of only 50 000 volts as compared with the author's 77 000 volts, and thus there would be less stress on the dielectric than in the suggested arrangement. If the intersheaths are used for conveying the power as well as for equalizing the pressure, the copper cannot be used so efficiently as if the whole of the power were transmitted at the higher pressure. As Mr. Holttum has pointed out, the actual power transmitted on each side of the system depends on the pressure from earth to the conductor and the current through the conductor (if the power factor is unity), and no arrangement could be more economical, as far as copper section is concerned, than to send the whole power through the conductor which is at the greatest pressure above or below the earth. In order to obtain an accurate estimate of the merits of the proposed system it ought, I think, to be compared with that shown in Fig. E which is really a six-phase system of transmission, lacking, however, the special arrangement of intersheaths given by the author. Intersheaths can, of course, be used with this arrangement, but in this case they would do nothing more than control the voltage gradient through the dielectric. If the author will compare his system with the one indicated above, I am sure that he will find that a greater cross-section of copper will be necessary in his system than in that shown in Fig. E.

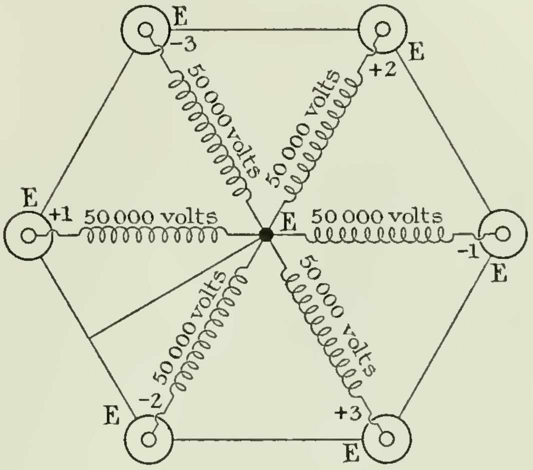


Fig. E.

**Mr. J. W. Warr :** Considering the new method from the consumer's point of view, I notice that the single-phase transformers will be designed at only 0·7 power factor, whereas, under existing conditions, the figure is 0·8. The power factor at the distributing centre determines that throughout the whole of the distribution system, even to the consumer's terminals. During the past 12 months there has been considerable discussion on the correction of power factor, and it has been generally agreed that the consumer must help the supply authority by keeping the power factor within reasonable limits. In the first place it would be interesting to note what the power factor will be from transformers originally designed at 0·7 when they are subjected to an inductive industrial load of comparatively small magnitude. For instance, in the present three-phase systems of distribution it is quite a common condition with a comparatively small load of 500 kW for the power factor to be between 0·65 and 0·7. Unless the electrostatic capacity of the cables raises the power factor, the consumer will be further penalized by having to compensate even more than at present. The figures suggest that a cheaper system of transmission is to be the result, but I consider that we should not sacrifice too much in this direction if the new proposals are in any way complicated. There is at the present time sufficient complication in connection with large distribution networks. The question of reliability is another important item from the consumer's point of view, particularly in certain industries. Inconvenience and endless expense are occasioned by an interruption at the distribution or main generating centre. A 20-minute failure will generally set the industry back for a whole day, and on these grounds, and on account of complicated switchgear, breakdowns are more severe than with the lower pressure supply. From the mains engineer's point of view the proposed system is no doubt a complicated one. Any mains engineer knows quite well the care and thought that is necessary in looking after a large network. Whatever method of distribution is employed some fault will develop, a failure of insulation producing a short-circuit either between conductors or to earth. Then I notice that there is a question of the distance apart of the single-core cables. Providing the distance between the centres does not exceed 7 in., the sheath losses will not be perceptible, but I should like to point out the space that is generally available in public streets for lighting and power cables. Frequently diversions have to be made for accommodating even the smallest high-pressure cable, and my experiences have been such that the direction has been a cause of great anxiety. Where there is already in existence a large network of cables, Post Office telephone cables, hydraulic mains, water mains, gas mains, etc., the available area is very restricted, and I doubt whether the author will succeed in getting through the thickly populated areas which must be traversed when laying trunk mains to the rural districts. At this point I should like to turn back to the comparative costs (see Appendix E) of the 30 000 and 100 000-volt systems. Apparently the great saving between the relative systems is shown to be in the laying of the underground cable. I notice, however, that in Scheme "B" (100 000 volts) there has been no special item set aside for excavating and reinstating the streets, as shown in Scheme "A" (30 000 volts). Are we to understand that the £400 000 for cables includes the excavating and reinstating? I would suggest that ample margin should be left for contingencies when dealing with a group of cables as proposed, compared with that in the case of an ordinary three-core cable. It is often only with difficulty that one or two three-core cables can be adopted in some roadways. Diversions have proved in the past to be more expensive on these grounds, and ample margin should be made.

**Mr. F. Mercer:** The author has described an intersheath cable to be used in conjunction with a special system of generation which is intended to make more economical use of cable space than is the case at present. Such a cable, however, is less efficient than a single-core cable having approximately the same cross-sectional area. A single-core 57 700-volt cable having the same diameter of core and thickness of dielectric as the one illustrated in Fig. 1, but having 0·422 sq. in. of copper in the core instead of 0·185 sq. in., should convey a current of 575 amperes without undue temperature-rise (assuming 9-in. centres). At 0·8 power factor this represents a carrying capacity of 26 500 kW per cable, which is more than 100 per cent better than the anticipated performance of the intersheath cable in Fig. 6 which, including intersheaths, has the same cross-sectional area of copper. The following points illustrate some of the disadvantages of intersheath cable: (1) Capacity currents necessitate a very appreciable cross-sectional area of copper for the intersheaths alone; (2) when used for conveying power the intersheaths are operating at lower voltages than the central core and transmit correspondingly less power for a given amount of copper; (3) space occupied by the intersheaths might be usefully occupied by dielectric; and (4) the permissible voltage gradient for the dielectric near the central core or the intersheaths is lower than for a single-core cable, because a thin dielectric necessitates a higher factor of safety. In connection with the table of comparative costs given in Appendix E, it is difficult to understand how 10 three-core 30 000-volt cables are expected to cost £1 000 000 for a 30-mile run, or £100 000 per cable, whilst 6 intersheath cables of approximately the same cross-sectional area are estimated at £400 000, or £66 700 per cable. A more valuable comparison would have been afforded if the estimates given in this appendix had been for the author's six-phase/three-phase scheme and for a three-phase single-core cable scheme, the operating pressure in each case being 100 000 volts.

**Mr. A. M. Taylor** (*in reply*): Mr. Malpas asks why I introduce an intermediate lead sheathing below the outer conductor of the cable. This outer lead sheathing was for the purpose of providing a means whereby the impregnation of the cables could be done in two stages, but a subsidiary purpose is served as indicated at the top of col. 1, page 229. The lead sheathing can, of course, be suppressed if found unnecessary for the manufacture of the cable.

With reference to Mr. Malpas's remarks as to the cost of the capital charges on the transmission line, I think there is no doubt that instead of 0·55d. per kWh he really means 0·055d. If the transformers, which are common to any system of lin transmission, are omitted, the cost is only of the order of 0·037d. This correction would alter his figure from 4·4d. per kWh on a 250-mile line, to 0·44d. This, however, is not all that may be said for the underground transmission, because from information received from one of the leading cable manufacturers it now seems to be practicable with this system to run the pressure up to 150 000 volts and with the same six cables to transmit 200 000 kW. On this basis the initial cost of the capital charges on a 30-mile transmission line would amount to only 0·018d. per kWh, and this would compare quite well with the 0·16d. quoted by Mr. Malpas for the much longer overhead line.

Mr. Holttum's preliminary remarks are partly correct and partly based upon a fallacy. It is capable of easy proof that the voltage in the load circuit which traverses the outermost intersheath is 60 000 volts, however near the outermost intersheath may be to the outside lead sheath of the cable, whereas it is demonstrable that in the arrangement shown in Fig. 5 the voltage transmission would be reduced to a ridiculously small amount if such a position were postulated for the lead sheathing. The small diagram (IV) at the left-hand bottom corner of Fig. 9 would have shown Mr. Holttum that it was practicable to increase the above-mentioned 60 000 volts, if necessary, to 80 000 volts, so that it is quite incorrect to say that any gain in redistribution of voltage gradient in the dielectric must necessarily be counterbalanced by a lower effective working voltage of a portion of the copper.

With reference to the cable shown in Fig. 13, the protection afforded by the extra intersheath can, if desired, be continued right up to and into the joint boxes. Mr. Holttum proceeds to demolish, one by one, the "conclusions" at which I have arrived (these have been superseded by others which will be found in the paper as printed in the *Journal*). He passes by the first four items with the remark that they emphasize reliability only, and he suggests that an ordinary three-phase system is just as good on this point. I admit that it is at 30 000 volts, but I have shown in the London discussion that the two systems cannot compare in point of view of capital outlay when powers of 100 000 kW transmitted over 30 miles are considered. He says that conclusion (5) applies to any three-phase cable. It does so in a degree, but the charging current, being in my system approximately double what it is in a three-phase cable, gives corresponding advantages for the purpose considered.

Mr .Holttum dismisses conclusion (6) in a very cavalier fashion, but I submit most definitely that instead of the gains of intersheath being compensated for by the reduced power transmission per square inch on a section of the cores, he has entirely ignored the extent of the gain effected by the use of intersheaths and by the separating of the cables, which in single-phase "intersheathed" cables gives my system an advantage of practically *three times* that of a plain three-phase system, as regards the E.M.F. which may be applied. Now, even if the reduction of the voltage on the currents passing through the intersheaths were 50 per cent, this would still only affect one half of the load (the other half being transmitted through the central cores), and, therefore, is only equivalent to a reduction of voltage of 25 per cent on the whole system, whereas I have just intimated that the *gain* in voltage by the use of intersheaths combined with single cores is 200 per cent.

Mr. Holttum next suggests that conclusions (7) and (9) appear to require further explanation, and in any case are light-load advantages only and can be obtained in an ordinary system by switching cables in and out. The advantage of reducing the capacity current at low loads is so important that in the United States several of the large generators employed in power transmission have had to be made considerably larger than they otherwise would have been, solely because of the supply of large charging current. The idea of switching in and out a large number of cables to adjust the capacity current is not practicable. On 100 000 kW transmission 16 cables would be required and the number of switches to be operated would be 32.

Mr. Holttum considers that conclusion (10) is of no particular advantage, and I am prepared to grant that with an ordinary three-phase system the point is certainly not one of much moment, but I have already shown elsewhere that an ordinary three-phase system cannot compete, from the point of view of capital outlay, with my proposed arrangements, at powers of over 50 000 kW.

As regards conclusion (11), he suggests that there is no gain over ordinary three-core cable from the point of view of the amount of waste room in the cable, and suggests that the economy of three-core construction will compensate for this. I can only say, with regard to the latter, that the estimates which I have obtained from the cable makers prove the contrary. In this connection I suggest that he refer to my remarks in reply to Mr. Sparks in the London discussion. In the same connection he implies that the 100 000-volt single-core cable would compete equally well on this point, and this I am prepared to concede, but in this case I submit that conclusions 2, 3, 4, 7, 8, 9 and 10 (particularly the last-named) have all to be considered in this connection, and there is still more to be said than has been embodied in the "conclusions." Mr. Holttum suggests that my conclusion (12) is merely negative. This is hardly fair, because if the point can be established it represents great possibilities which the present makers of cables have not seen their way to take advantage of, or to suggest. He suggests that all the advantages claimed are quite wiped out by the three disadvantages mentioned. As regards these disadvantages, I would say that the first is somewhat of an advantage, if my system of capacity current can be successfully adopted. The second disadvantage will not obtain when the cables are laid along the sides of railways in the manner which I propose; only three cables need be laid together, the other three can be put on the other side of the railway, and in fact any distance apart that is desired, from the first three. It follows, therefore, that it is only necessary that three cables should be arranged in "triangle" regulation to one another, and this is perfectly easy. I trust, therefore, that I have met the whole of Mr. Holttum's criticism, and that there is no outstanding point which I can be said to have ignored.

With reference to Mr. Clothier's remarks about the superposed currents shown in Fig. 7, he will, I think, find his difficulties cleared up by a reference to Fig. D, given in my reply to the London discussion. He will there see the source from which is derived the supply spoken of as differing by 30 degrees in phase from the two topmost corners of the hexagon. He will see that all the circuits are quite easily derived from one common system of low-tension three-phase busbars, and will realize that they are all equally easily reconvertible to a common system of low-tension three-phase busbars at the receiving end. Mr. Clothier is correct in supposing that the reason for the omission of a comparison of the cost with that of a straight 100 000-volt single-core cable system was that these cables cannot at present be manufactured. Even if they could be manufactured, however, there are numerous reasons why the supply through the system proposed by the author would be very much more reliable in actual working, some of which are given under the heading "Conclusions" on page 232. It is submitted that, even if the plain single-core 100 000-volt cables can be manufactured, the proposals given in the paper will still be very much more satisfactory for reasons which have been adduced in various places during the discussion.

With reference to Mr. Clothier's remarks as to the number of transformers involved, the reason is one that would apply partly to single-core cables also, and is due to the large amount of leading kVA capacity available, *unless* the lagging component of the consumer's load can be effectively utilized in the manner proposed by the author. In this latter case, as is indicated on page 238, a saving of £75 000 would be involved in the reduced capacity of transformers. The finance of the estimated capital saving of £77 800 is, in my opinion, most essential to a proper understanding of the reasons for the selection of 10 cables of 0·25 sq. in. section as against the 6 cables considered in the proposed system. It is quite true that I omitted the interest on the money invested, but if this be taken into account, and if the 25-year life of the cables be also taken into account, the capitalized value of each 1 per cent loss in transmission can be shown to be of the same order as the figure above given.

With reference to the last point brought forward by Mr. Clothier, namely, that the success of the commercial application of the system proposed depends largely upon the possibility of a suitable single-core non-intersheathed cable being produced, this point has already been dealt with. Briefly, it may be said that a non-intersheathed single-core cable which, for an equal diameter of cable, can be operated at the same voltage as the intersheathed system, is not likely ever to be introduced Mr. Clothier seems to have lost sight of the fact that it is not necessary that one half of the power should be put through the six-phase system, and that if, for instance, one quarter of the power were put through the latter, the voltage of transmission would be equivalent to a voltage of 90 per cent of the full central-core voltage taken over the combined system.

In reply to Mr. Mallinson, I would refer him, in connection with overhead transmission, to my reply to Mr. Malpas, also to the discussion at Newcastle. With regard to guaranteeing the cables for only one year, it was I myself who fixed this period, believing that it was hopeless to expect the cable makers to guarantee a new cable, about which they knew nothing, for a longer period.

Mr. Mallinson's remarks with reference to the joint shown in Fig. 13 are made on an entirely wrong supposition. He is assuming that I am considering the running of cables along ordinary roads, whereas I am considering their running on short supports some 18 inches above ground on the two sides of a railway line, and where the position of the joint can in most cases be adjusted quite easily. I have suggested elsewhere that a few drums, of lengths slightly greater and slightly less than normal, which might be used in special circumstances, could be supplied. With regard to Mr. Mallinson's remarks that the three disadvantages cited are equally as vital as the advantages cited, and that particularly No. 2 is a serious one, I would remark that my proposals involve only three cables being kept in close proximity to one another; the other three cables could be placed many yards apart from the first three, since each set of three balances out its own field. This also applies to his difficulty about keeping them cool, and to his difficulties about the large cross-section of the main required. Moreover, 16 three-core three-phase cables will certainly take up more street room than would my six cables.

In reply to Mr. Fuller, the lantern slide which I exhibited connecting resistivity with temperature was based upon alternating currents, and I note that it is practically in accordance with a curve very recently given by Prof. Delmar. I do not see the point that, because the power factor can be kept below 0·01 over the working range of temperature, the dielectric resistivity losses can consequently be ignored. If the figure taken for the resistivity in the calculations at the end of the present paper is in the least degree near the mark, the resistivity loss is quite a serious one at the high temperatures, and what we have to consider is not merely the *estimated* range of temperature, but the temperature that may obtain when, through some breakdown of a parallel system, perhaps double the normal load is passed through the remaining system, and it may occur at the time of greatest summer temperature.

In reply to Mr. Fuller's remarks regarding intersheaths, I have already taken up the point of the question of maximum stress in reply to Mr. Dunsheath (see page 248), and am strongly of opinion, after reading the whole of the controversy in America on this question, that we cannot afford to ignore the maximum potential gradient when it is a question of continuous working. With reference to Mr. Fuller's remarks that, owing to the voltages in my system being 60 degrees out of phase, nothing is gained as compared with non-intersheaths, I would point out that this has been dealt with in connection with my remarks in reply to Mr. Dunsheath, where I have shown that the loss due to the obliquity of the vectors is only 15 per cent, whereas the gain due to the use of intersheaths is 220 per cent. Mr. Fuller's remarks that the gain from the use of the intersheaths is negligible are therefore totally unwarranted by the results established in the paper and the discussion.

Replying to Professor Marchant, I would say that, on a 30-mile line, it is only necessary to introduce what he calls the auto-transformer arrangement (but which I submit is a misnomer) at the extreme end of the line where it forms a perfectly simple and practicable arrangement. Possibly Prof. Marchant has not had occasion to consider such a long line as this is and has consequently not fully appreciated the large amount of charging current to be transmitted, and how important it is that this should be transmitted under the full voltage.

It is quite true that such an arrangement as is given in Prof. Marchant's Fig. E would work perfectly well, but apart from the fact that the full 50 000 volts exists between the central core and the lead sheathing, there would be the difficulty of the junction boxes, in which there is nothing to give any hint of trouble until a total breakdown occurs at one of the latter. The same applies, of course, to the cable itself. Moreover, it is not yet an ascertained fact that cable makers are prepared to supply cables operating at 100 000 volts. Further, it appears that if a breakdown occurred in any one cable it would not only operate the trip gear on the one half winding of the transformer supplying that cable, but the other half winding (if on the same core) would probably be pulled out as well, which would instantly involve the shutting down of the whole system as a three-phase system, whereas under the arrangements I am proposing, with three self-contained hexagons working independently, the pulling down of one hexagon would only put that hexagon momentarily out of circuit, and a few seconds later one of the cables at least could be reinstated. Further, if the fault extended only as far as the outermost intersheath, the probability is that the whole six cables could still be employed after the momentary disconnection of the faulty hexagon. Prof. Marchant's remarks relating to the obliquity of the vectors are quite correct so far as they go, but I have shown elsewhere that it can be easily arranged that only 15 per cent is lost by this obliquity. I have dealt with the question of the use of intersheaths for the conveyance of power in my replies to other speakers.

In reply to Prof. Marchant's remarks that if I compare my system with that shown in his Fig. E, it will be found that the amount of copper is less in the latter, I am not disposed to question that there would be a small amount in this direction, but since taking up this general question of transmission I have ascertained that the amount of copper in the system is not the sole criterion of its cheapness, or the reverse, and the system shown in Fig. E, though interesting, cannot possibly compete with an intersheath system if the maximum potential gradient is to be accepted as any criterion at all for the safety of cable working over very long periods at the highest possible stresses.

I think that Mr. Warr is under a misapprehension as regards the question of power factor. The reason of my transformers being put in for a low power factor is solely on account of the large line-charging current, which affects the step-up transformers at the sending end very materially. If this charging current can be arranged in the way I propose, to benefit the system, then, instead of the consumer being penalized as Mr. Warr suggests, he will get a bonus on account of his poor power factor. Does Mr. Warr realize that the question of distribution is really not touched by my proposals and would remain exactly where it now is, since I revert back to ordinary three-phase currents at the substation ? His remarks as to the mains engineer's position also give me the impression that he is thinking merely of a ramified underground system operating at 100 000 volts, which is not my proposal at all. Similarly as regards the area required by the mains, this is because he is considering town distribution, and perhaps because I have not made it sufficiently plain in the paper that I am primarily considering transmission along the main lines of a railway between a super-power station and a general substation at the far end of the line, with possibly intermediate substations feeding the railway itself, but at considerable distances apart. This will explain why I have not included any item for the excavation of streets in connection with the system proposed, the reason being that the cables are merely assumed to be carried some 18 inches above ground on a light structure at the side of the railway, and no excavation is therefore necessary.

Mr. F. Mercer endeavours to show that by employing a cable such as shown in Fig. 1 of the paper and filling in the central parts of the central core with copper, the power can be put through in a much more efficient way than under my proposed system. I would say, however, that if one of the cables goes down, the whole system goes down, and therefore there is no reliability whatever about his proposal. Moreover, I have shown in my reply to the London discussion that a single-core unsheathed cable cannot compete with a single-core intersheathed cable, which latter can be worked at a voltage nearly 100 per cent greater for a given cable diameter and maximum potential gradient. As regards his remark that capacity currents necessitate a very appreciable cross-sectional area of core for the intersheaths alone, I would point out that by the method of transmitting the capacity current shown in Fig. 12, the current required to be transmitted through the central core is virtually identically the same as that required in the case of a single-core cable—in fact, with the 100 000 volt single-core scheme the kVA for charging purposes is 65 700, whereas in my scheme it is 61 200. These figures can be obtained from the calculations given in the paper. I have dealt elsewhere with Mr. Mercer's point about the intersheaths operating at lower voltages. His remark that the intersheaths occupy unnecessary space which could be usefully occupied by dielectric is also beside the point, because copper strip can be employed for the intersheaths. Apart from this, however, I have made calculations as to the actual difference in diameter of cable due to the addition of the intersheaths, which show that his statement is quite untenable as a serious objection. His statement that the permissible voltage gradient allowable is less where intersheaths are employed than for a single-core cable raises the whole question of maximum potential gradient, and I do not consider that to put the matter in this form is a fair statement of the question involved. After a careful perusal of the discussion before the American Institute of Electrical

Engineers on the various recent cable papers, all of which are, in my opinion, of high merit, I do not consider Mr. Mercer's statement to be fully proved, at any rate in the form in which it is given; *in fact in one place it is directly contradicted.*

With reference to the prices of the cables, I may say that I obtained prices from several manufacturers and I have neither given the highest prices obtained for the three-phase cable, nor the lowest prices obtained for the triple-concentric cable. With regard to Mr. Mercer's remark that it would have been better if a three-phase single-core cable scheme had been compared with the scheme put forward in the paper, I may say that there is not at present in existence a three-phase single-core cable scheme operating at 100 000 volts, and I am not certain whether I should have been able to get any guarantees for it in this country, but even if I had succeeded in this there is, in my opinion, no question as to the much greater reliability in operation of a triple-concentric cable the outermost conductor of which is at a potential not very greatly different from that of earth.

# DISCUSSION ON

# "DOMESTIC LOAD BUILDING."*

### SCOTTISH CENTRE, AT EDINBURGH, 9 JANUARY, 1923.

**Mr. R. B. Mitchell**: I have always been a believer in the cultivation of the domestic load, and I have said before on many occasions that the day may come when the domestic load will be of as great importance as the industrial load. It has a feature of continuity which the industrial load does not possess. We have just been passing through a time when the industrial load almost disappeared in the majority of undertakings in the country, and if those undertakings had had a good domestic load to keep them going during the dull times in industry, they would not have felt the effects nearly so much. In Glasgow the domestic load has been cultivated for some years past and we have achieved considerable success in that direction. We have now connected domestic appliances totalling 17 165 kW and the consumption due to these appliances amounted last year to 5 506 000 units. Also, we have in business premises appliances other than for lighting, totalling 15 080 kW. In looking over the paper, I consider the main point in it to be the question of tariffs. I think that the tariff is of the very first importance in developing the domestic load. If one has a suitable tariff, then it is quite right to have propaganda, but propaganda is useless unless one has such a tariff. I quite agree with the author's opinion on page 197 that the fixed charge should be sufficient to cover a consumer's normal lighting costs when the low unit charge is added. Further, I think that the fixed charge should be made high initially, in order that the running charge may be as low as possible. There is one drawback to that system of charging, namely, that to the ordinary consumer it is too great a change. He may have been in the habit of using electricity for lighting only, consuming, say, 50 to 200 units per annum, and paying a comparatively small sum for the service; and he is asked to promise to pay something like £8 10s. before he uses any electricity at all. I think that the ordinary man, particularly in Scotland, will hesitate before he takes on such a commitment. But there is another way of achieving the object: a tariff should be arranged, with a fixed charge and a low running charge, which will lead him on in steps in such a way that he will not notice the increase in his use of the electric service. I agree with the author that the fixed charge which he puts forward should cover the lighting units only—perhaps more than that—and that the demand of the heating and cooking appliances should not be taken into account in making up the fixed charge. It has been thought in the past by many supply engineers that the maximum demand for lighting was not sufficient—that the consumer possibly used a very small quantity of electricity for lighting with consequent low maximum demand—and perhaps 5, 6 or 7 kW for heating and cooking, and that this ought to be taken into account when fixing the maximum demand. It has been proved conclusively now that the domestic load is nearly always in its entirety an off-peak load. One has not to take into account the domestic load in thinking of the power station output in kilowatts. As regards the rate in Glasgow, we have adopted the principle that consumers are asked to pay for a certain number of units at the lighting rate, depending upon the size of the house, and all units consumed over the fixed quantity are charged for at the heating and cooking rate, which at the present time is 1d. per unit. The consumer can secure this rate even if only a very small domestic appliance is installed. He must have something, even if only an iron, but this gives him a start, and he adds to his installation and later on gets a cooker which, in 99 cases out of 100, converts him completely to an all-electric user. Then, if he wants to go still further and use electricity more liberally, he is ripe for a rate of the description put forward in the paper. I have applied to the accounts of a number of consumers in Glasgow a system such as the author explains, and I find that it can be superimposed on this rate with very great facility and works very well. I adopted a fixed charge such as he suggests, but I got the basis for it by taking a percentage of the rental, and I think that a figure of something like 10 or 12½ per cent would be appropriate. I am quite sure that by and by, with a fixed charge of that amount and a running charge of ½d., a tremendous development could be made in the domestic load. By taking 10 per cent plus ½d., and superimposing that on the rate in use in Glasgow, we find that for the small user—the man with a rental of, say, £35—with a fixed charge of £3 10s. plus ½d., he would be ready to change over to the new system when his consumption reached 900 units per annum. Similarly, consumers occupying houses rented at £40, £60 and £70 per annum would be ready for changing to the new system when their consumptions reached 1 200, 1 400 and 1 700 units respectively, with an average price of 1·49d. per unit. If they adopt the new system and use, say, 3 000 units the average rate for all electricity used is 1·06d. per unit. In Glasgow, we have gone almost as far as any other undertaking in developing the cooking load, and we have now 400 cookers on hire at a rental of £2 per annum, which is less than the 20 per cent figure put forward by the author. Some curves (see Fig. B, page 394) which I have had prepared show the demand from domestic consumers in residential areas in this city. There is one point of difference in the domestic load curves in the paper, as compared with what might be expected in Scotland, in that the author's curves show a considerable load on Sundays. Unfortunately we cannot expect that here.

---

* Paper by Mr. W. A. Gillott (see page 197).

**Mr. E. Seddon:** There can be no doubt that we have only touched the fringe of the possible domestic load which can be obtained by a well-organized advertising scheme. Electricity departments should be prepared to hire out apparatus to prospective heating consumers who can make trials of cookers, etc., without incurring much expense to themselves. The gas industry obtained their valuable domestic load from such a scheme. In Edinburgh we have not yet taken any energetic measures to secure this load, but we are now making a move in that direction. It seems to me that it will be unwise to push the use of heavy appliances where new consumers are already using gas, but that we should, in the first case, get the consumers interested in light articles such as grills, irons, etc., which will give them confidence in the use of electric heating apparatus. The development of this load is very much bound up with a suitable tariff. I look forward to the time when a suitable flat-rate charge can be made for all domestic supplies, with a minimum charge per lamp installed ensuring a reasonable revenue from every consumer. I think that domestic consumers with a heating load well established will provide a load factor equal to that of most industrial concerns and can be offered equally good terms. The curves shown by the author are taken from specially equipped houses, and I think that the consumption is higher than one would expect from the average consumer with the same appliances. Nevertheless, the paper indicates the amount of business that can be obtained from the small householder. Finally, although slot meters may be quite suitable for artisan dwellings they cannot be recommended generally.

**Mr. R. Hardie:** I have to express my entire agreement with the author. Glasgow has been for some time past proceeding generally on the lines laid down, and results indicate that these are sound. We have discovered that there is a vast desirable heating and cooking load awaiting exploitation and obtainable with the minimum of capital expenditure. The electric cooker alone, in use three times a day all the year round, will convert a non-paying lighting consumer into a profitable one, and this without additional expenditure on feeders, mains or service cables. The folly of having domestic services lying inactive for most of the day all the year round (and all day in the summer months) must be recognized. With regard to rates, we in Scotland dare not suggest the author's figure of 8d. per unit for lighting, nor do we approach the 1½d. rate mentioned for cooking. Obviously the cooking rate must be made sufficiently attractive to secure business. In other words, the cooking rate should be fixed at that figure which local experience decides is as high as can be secured for a service that is competitive with coal and gas. In some parts of the country 1½d. may suffice—in others 1d. per unit—while in a few supply areas favoured with large and economical generating units and with adjacent supplies of low-priced coal the ultimate figure may be as low as ½d. I agree with the author's contention that every official, nay every employee, in an electricity supply undertaking should possess knowledge of domestic electrification based on actual use of apparatus in his own house. The advertising value of this would be far reaching. The lack of definite performance data on the cooking load has hindered the proper development of this business, but the information contained in the Billingham curves, presented by the author, and the fact that these are confirmed by the figures obtained in Glasgow and elsewhere, should do something towards removing doubt from the minds of electricity executives, and should encourage them to go forward and acquire a larger share of the domestic business. Another branch of propaganda urged by the author, the "Electric Home" exhibit, is deserving of more general adoption. Its educational value is far reaching, and probably no other form of advertising will do more to bring home to the public the desirability of having their houses adequately wired.

**Mr. A. Mears:** The lighting and industrial loads have already been acquired in a very large measure by electricity stations, but the heating and cooking load to a large extent represents a new field of development calling for special consideration. In Edinburgh we have been unable to do much to develop this load owing to a shortage of generating plant, but this con-

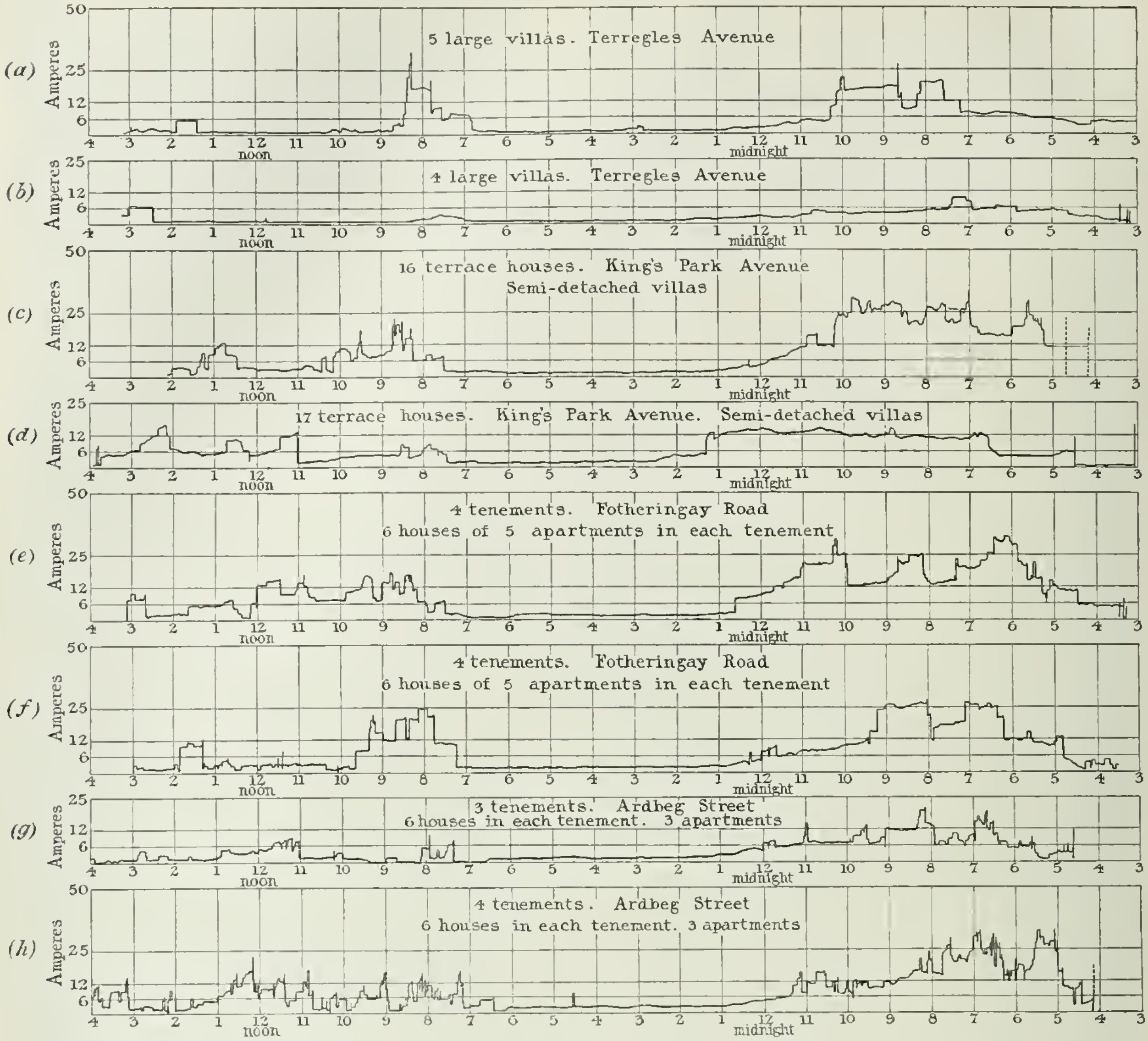


FIG. B.

*Total installation.*

| | | amps. |
|---|---|---|
| (a) | 173 m.f.* lamps | 36 |
| | 12 radiators | 77 |
| | 5 irons | 10 |
| | 4 vac. cleaners | 8 |
| | 1 cooker | 26 |
| | | 157 |
| | 50 amp. shunt: max. 20 amps. | |

| | | amps. |
|---|---|---|
| (b) | 205 m.f. lamps | 44 |
| | 8 radiators | 74 |
| | 2 irons | 4 |
| | 1 kettle | 2 |
| | | 124 |
| | 50 amp. shunt: max. 8 amps. | |

*Total installation.*

| | | amps. |
|---|---|---|
| (c) | 288 m.f. lamps in houses | 59 |
| | 17 radiators | 136 |
| | 11 irons | 22 |
| | 2 kettles | 5 |
| | 2 hire cookers | 52 |
| | | 274 |
| | 50 amp. shunt: max. 32 amps. | |

| | | amps. |
|---|---|---|
| (d) | 323 m.f. lamps | 66 |
| | 1 cooker | 26 |
| | 13 irons | 26 |
| | 3 radiators | 24 |
| | 2 kettles | 5 |
| | 2 vac. cleaners | 4 |
| | | 151 |
| | 50 amp. shunt: max. 13 amps. | |

*Total installation.*

| | | amps. |
|---|---|---|
| (e) | 324 m.f. lamps | 66 |
| | 1 cooker | 26 |
| | 1 grill | 6 |
| | 16 irons | 32 |
| | 11 radiators | 88 |
| | 8 vac. cleaners | 16 |
| | 1 kettle | 3 |
| | | 237 |
| | 50 amp. shunt: max. 32 amps. | |

| | | amps. |
|---|---|---|
| (f) | 327 m.f. lamps | 67 |
| | 1 cooker | 26 |
| | 13 radiators | 104 |
| | 12 irons | 24 |
| | 6 vac. cleaners | 12 |
| | 2 kettles | 6 |
| | | 239 |
| | 50 amp. shunt: max. 26 amps. | |

*Total installation.*

| | | amps. |
|---|---|---|
| (g) | 108 m.f. lamps in houses | 23 |
| | 9 m.f. lamps in stairs | 1·5 |
| | 4 m.f. lamps in street | 1 |
| | 13 irons | 26 |
| | 3 radiators | 28 |
| | 2 hire cookers | 52 |
| | | 131 |
| | 50 amp. shunt: max. 14 amps. | |

| | | amps. |
|---|---|---|
| (h) | 144 m.f. lamps in houses | 30 |
| | 12 m.f. lamps in stairs | 2 |
| | 2 m.f. lamps in street | 0·5 |
| | 14 irons | 28 |
| | 3 radiators | 24 |
| | 6 hire cookers | 156 |
| | | 240 |
| | 50 amp. shunt: max. 26 amps. | |

* Metal filament.

dition has now disappeared and we find the domestic load increasing rapidly. The latter can, however, only be obtained by fixing a suitable tariff which must be kept as low as possible. It appears to me that simplicity should be the keynote of it, as a tariff that calls for a calculation with each consumer as to the ultimate rate per unit which he will pay for electricity used for heating and cooking is not appreciated. On the basis of simplicity a flat rate per unit for heating and cooking consumptions appeals to the consumer. It is true that this means a separate circuit and meter for the heating and a certain extra expense in wiring, but after all, is the expense so much more than that of a combined lighting and heating installation if the latter is properly arranged, the lights being fused independently of the heaters so as to give proper protection for the lighting? In Edinburgh our charges for lighting and heating are on the flat-rate system and, naturally, separate circuits are required for lighting and heating, but up to the present this has not proved a drawback to the installation of heaters in the larger houses where the heating load is likely to be of reasonable amount. Apart from this question of expense of the extra circuit there is no reason why a flat-rate tariff cannot be arranged to give as cheap result for heating as any other system. It is found that the variation in the annual consumptions for lighting purposes in houses of similar size and character is very considerable, and under most of the two-part tariff rates a consumer who is below the lighting average fails to get the same advantage for his heating rate as one who is much above this average. The simplicity of the separate flat rate for heating undoubtedly appeals to the average consumer, though it may be possible in the future to educate the consumer to some two-part tariff. In Edinburgh the case of the small consumer whose heating appliances are mainly of the lamp-holder variety and whose consumption is so small that it is not worth a separate circuit has been met by charging him an arranged quantity of units for lighting, and all units recorded in excess of this quantity at heating rate. This arranged quantity is based upon past records and general averages, but the method is really an attempt to give him the benefit of two circuits without running the second one. It is the system originated in Glasgow on maximum-demand lines, but adapted to the usual flat-rate method of charge in use in Edinburgh. On the whole it is satisfactory, but, like all systems which depend upon the fixing of a quantity not accurately known, it does not please every consumer. The two-part tariff on the maximum-demand basis, where the demand for lighting only is taken, suffers from the same drawback, as this demand as a rule cannot be known accurately. Apart from the question of tariffs, electric cooking with electric ranges cannot, I fear, advance much without a system of hiring by supply authorities. Not many consumers will experiment owing to the cost of the ranges and the probability of high maintenance costs. The interest which the public take in electrical appliances of all kinds in exhibitions is a very good sign, but there is no doubt that a large amount of educational work remains to be done before the domestic load develops to any great extent. A very interesting figure in connection with this subject is the actual diversity factor of this class of load quite apart from the question of the proportion of the heating load that is included in the lighting peak, i.e. the sum of the maximum demands of the heating consumers divided by the maximum demand made on the station. The author suggests a value of 9 for this figure, but that is surely much too high. This figure is of considerable importance when the question of price per unit is being arranged. The principal feature of the domestic load is the improvement on the annual load factor of the station that it should produce, and on this ground it is to be encouraged as much as possible.

**Professor F. G. Baily:** One reason for the slowness with which domestic electric appliances are gaining recognition seems to me to be the initial expense. A mere kettle costs some 30s. and a vacuum cleaner £15, and people hesitate to spend this if they have any doubt of its suiting their convenience. Hence I advocate facilities for hiring articles of this kind for a short period. Sales would almost always follow when the consumer had realized the resulting saving in trouble. This is even more important in the case of electric ovens, where the ovens and power circuits will cost £30 to £50 and will involve a complete rearrangement of the kitchen department. A consumer should be able to hire an oven and temporary wiring and switches, which can be installed without disturbing the kitchen range, and when fully satisfied he will proceed to a complete change; but it is demanding much faith in electricity to propose a drastic change in so vital a part of a household as the kitchen. Another point is that of hot water. It is futile to expect electric energy to compete with a properly constructed hot-water boiler, which is a highly efficient apparatus and gives opportunity also for some central heating. An all-electric house may be satisfactory in a warm climate, or in a small flat, where convenience far outweighs expense, but I can only regard it as a fad in an ordinary household in the northern and eastern parts of Great Britain. It must be remembered that while undoubtedly a considerable portion of the heat of the coals in an open grate or kitchen range goes up the chimney, by no means all of it comes out at the top. Much of this escaping heat reappears in the upper rooms and passages, which without this would be chilly and damp. The total heat of electric energy at 2d. per unit costs 40 times as much as that of coal at 40s. per ton, so for straightforward heating there must be very strong reasons for adopting the more expensive agent.

**Mr. W. J. Cooper:** I cannot understand the attitude of certain business men towards the two-part system of charging. No one knows better than these same business men what on-cost charges are, yet, when an electricity supply authority proposed to charge their product on the basis of an on-cost charge plus a charge per unit used, there was difficulty in getting them to understand and to appreciate the system. We can overcome the objections to a certain extent by expressing the standing charge in banks of units, on the lines of the Glasgow domestic heating tariff.

**Mr. A. S. Hampton:** Amongst all the suggestions with regard to tariffs I have not heard any in the shape of a tariff based on a charge of so much per room plus a running charge per unit used. This would only mean one meter, and a very low rate per unit might be reached. Everyone would understand a charge of this kind. There is a difficulty in getting the average householder to see the advantage of two meters or the two-part tariff. I admire the Glasgow Corporation rate; it seems to be very fair and it only requires one meter. It is practically the same as the rate which I have suggested, viz. an annual charge per room and a very low flat rate per unit. It gets rid of the two-circuit wiring, which is some considerable advantage, and it allows the easy use of the small power appliances.

**Mr. A. Ogilvie:** The subject is of much importance to public supply companies and, in its development, benefit will accrue to the consumers. The two-tariff system is attractive and fair to the consumer, while it is reasonably remunerative to the supply company. I would, however, leave the main questions raised to those more intimately and directly interested, and confine my few remarks to one feature in the propaganda proposals, namely, what is to be the precise position of the local electrical contractors in connection with the sales and work which it is suggested should be carried out by the public supply undertaking? It is observed on page 201 that the contractor would be properly dealt with in regard to any sales effected and I should like to ask the author if he would indicate (1) How it is proposed to protect the contractor, and (2) how it would be possible to ascertain the contractor responsible for each individual sale effected by the public supply company from their showrooms. Again, it would appear from the remarks on "Showrooms" that it is intended that the public supply company should carry out electrical work in the consumer's premises. If so, then the whole question of municipal trading arises, and while it may at first sight appear to be a side issue on the larger question raised by the paper, still it is a most important one for those ratepayers engaged in the electrical industry generally. (This aspect, of course, applies only to cases where the municipality control and operate the electrical undertaking.) The question of a municipality utilizing ratepayers' money for carrying on a commercial enterprise in direct competition with the ratepayers engaged in that industry, is a large one and one which I venture to think should not be allowed to enter into any propaganda work under domestic-load-building schemes. So long as consumers can obtain their requirements (both labour and material) at reasonable terms from the local contractors—which is almost invariably ensured by local trade competition between contractors—then I suggest that domestic-load-building schemes would, in the end, be best served by the electrical undertaking confining their efforts to demonstrating in their showroom the many and varied uses to which electricity may be put in domestic and industrial fields, leaving the local contractors to supply the consumers' requirements thereafter. The author's views on this point would be interesting.

**Mr. D. S. Munro:** None can challenge the wisdom of the advice that all those dealing with domestic supply should themselves have practical experience of its working in their own homes. To this may be added the provision of an experimental room at the power station or other showroom where each cooking or other device may be demonstrated by the officials thus trained at home. The author refers to records. There is need for more records available to the whole trade, records of actual facts, not faked for competitive purposes. Some of these would refer to results obtained by trial of this or that appliance as well as to guiding figures obtained by recording group results such as those indicated on page 198 of the paper. The author gives the annual units used per kW installed as 360, and the kW installed as 65. 360 × 65 = 23 400 units. But, a few lines below, he gives that portion which falls on the peak as 5 kW demand and the units on this demand as 3 240. 3 240 × 5 = 16 200 units. Perhaps I have not understood the figures, but they may possibly be made clearer so that the load factor of this little group of consumers may be ascertained. As regards a two-part method of charging for energy, customers are not fond of it. If it is governed by a demand indicator it tends to restrict use. If it is a fixed kW charge varying with kW installed it makes the consumer reluctant to install lamps of occasional convenience, or to add further appliances—such as a washing machine which is intended only for occasional use. If the fixed charge be calculated from the floor area or the rated valuation of the house it is open to objection on other grounds. Yet some sort of two-part charge is fair and will become necessary. In some cases a low average consumption is predetermined, and all current up to this amount is charged at a high figure per unit, all further units for any purpose being charged at the lowest possible price per unit. This method has several incidental advantages—one meter and one house wiring system, for example—and I should be glad to hear opinions as to the fairest method of arriving at the number of units to be charged at the high rate. One of the objections to a fixed charge arises when a house is empty for a considerable part of the year. The figure in Scotland for sundry units would probably differ widely from that in England, though not so much now as formerly. As a contrast to the methods of a fixed charge per quarter or per kW maximum demand, there are suppliers who not only charge a special rate per unit for cookers and the like but actually present the consumer with something towards the first cost of the appliances which are going to increase his maximum demand. Merely noting the satisfactory point emphasized by the author that this class of individual demand has a comparatively small effect on the whole system peak—though it is easily possible that a small town of big residences might be doing much cooking for dinner at the very time of heaviest lighting demand—I pass on to add a word or two about the sale or rental of appliances by the suppliers of electricity. If this system be necessary to promote output of electricity it might be equally justifiable for the suppliers to rent wiring installations. So I ignore the unfairness of such forms of competition and merely remark that it should pay suppliers well to support around them that large body of influential canvassers represented by the electrical contractors.

**Mr. W. A. Gillott** (*in reply*): With few exceptions this discussion has been upon similar lines to those at other Centres, and in consequence the replies already given to speakers in those discussions dispose of many of the questions now raised. I therefore propose to confine my reply to the items of special mention.

Mr. Mitchell refers to the suggested fixed charge of £8 10s. causing consumers to hesitate to adopt such a tariff, but this sum would cover a household with 1 kW of lighting installed, and of course is adjusted to suit the capacity of each lighting installation. The rental value of such a household in Glasgow would doubtless be approximately £80, and under Mr. Mitchell's proposed tariff the fixed charge would be similar. It is indeed very encouraging to receive confirmation that Scottish returns of domestic load prove cooking and heating to be practically " off peak " loads to such an extent that it is not necessary to consider them when assessing a fixed charge in the tariff. The load curves of Mr. Mitchell's Fig. B indicate that the demand is approximately 10 per cent of the total installed watts.

Mr. Seddon and Mr. Mears mention the use of small appliances from a lampholder and appear to lean to the view that it is preferable to start a consumer with such devices and gradually lead up to the complete cooker. I have no hesitation in saying that the complete cooker is such a satisfactory proposition that where the supply is offered at 1½d. per unit or less one can with every confidence thoroughly recommend a consumer to install the complete article from the commencement, and I suggest that if the business is handled upon these lines, good results will be secured by all parties concerned.

Mr. Hampton refers to the tariff with its fixed charge based upon the floor area, as in Dundee. A reference to this system is given on page 216.

Mr. Ogilvie asks what is the position of an electrical contractor in a propaganda campaign, and whether the supply authority should carry out the installation work. This subject is such a highly political one that I am afraid it cannot be properly dealt with here, but I would repeat that I firmly believe in the principle of straightforward co-operation, either side not expecting too much from the other, but each working with one object in view, i.e. to give good service to the client. This will result in the establishment of good general conditions between the contractor and the supply authority.

Mr. Munro asks for further details regarding the first set of figures given on page 197. The actual details as to the results obtained under test are given below, and it will be found they are slightly different from those previously given, as only round figures were quoted.

From a study of the returns of 13 consumers it was found that the average kW installed was 5, the maximum being 6 kW and the minimum 3·2 kW. The *average* maximum demand per *individual consumer* was 3 kW. The average units consumed per annum per consumer were 1 800, and the sum of the consumers' maximum demands represents 181 amperes. The maximum result caused by the 13 consumers was 75 amperes, therefore the diversity factor among these 13 consumers is $181/75 = 2 \cdot 41$.

The amount of resultant load from these 13 consumers that fell upon the system peak was 20 amperes, which occurred at 12 noon, when the system curve was falling. This equals 0·285 of the maximum resultant load, so that the units consumed per kW demand on the system peak are $360 \times 2 \cdot 41 \times 3 \cdot 75 = 3\,253$.

The figure of 360 is obtained by dividing the total kW installed into the cooking units consumed by the 13 consumers. From these figures it will be seen that the diversity factor in this instance is $2 \cdot 41 \times 3 \cdot 75 = 9$. The figure of 3·75 is the ratio between the 75 amperes resultant demand, and the 20 amperes that fall upon the system peak.

# DISCUSSION ON

# "THE PROPERTIES OF THE DISTRIBUTION FACTOR OF ARMATURE WINDINGS." *

**Mr. A. E. Clayton :** At the present time considerable importance attaches to the higher harmonics present in alternating E.M.F. and current wave-shapes, and there is reason to expect that importance to increase rather than to diminish. As a result, the values of the distribution factors for these harmonics are of much moment to those interested in the design of alternating-current machinery. Values of these factors for various normal slottings have been tabulated by, amongst others, Dr. S. P. Smith and Mr. R. H. Boulding,† and by Mr. B. Hague.‡ Such tables, although very valuable, are, as stated by the authors on page 865, limited to a few common cases, and are therefore to a certain extent limited in their application. It is thus undoubtedly desirable to have the data available in a simple form suited to perfectly general application, either in the form of tables, or in the form of graphs. The paper is therefore of great interest ; to me it is of particular interest as some time since I also was intrigued by the problem of representing these factors in a simple, graphical manner.

The graphs in Fig. 3 indicate clearly the effect of the number of slots per group, $q$, upon the value of the distribution factor for any particular value of the equivalent angle of spread of the winding, $m\sigma$. From the graphs it is possible to obtain the value of the factor under any given set of conditions. (In this connection, the use of 12 ordinates per range of $\pi$ is to be deplored. Such a choice is only suited for the quite normal case of three-phase and two-phase windings, i.e. the few common cases mentioned above. The choice of 10 ordinates, or, better still, 18, is more suited to general application.) For practical purposes, however, the authors put forward a series of graphs in Figs. 4 ($a$) to 4 ($d$), in which values of the factors for harmonics up to the seventh order are plotted against the angular phase-spread expressed in degrees. These form a valuable set of graphs about 30 in number, but limited to harmonics up to the seventh order.

In developing the mathematics of the subject the authors have expressed their results in terms of the angular spread of the phase group ; simpler results are possible if they are expressed in terms of the angular slot-pitch. For example, with $q$ equal vectors displaced by $2\gamma$ between successive vectors, it is at once obvious that the numerical value of their resultant will be the same as that when the displacement is $2M\pi \pm 2\gamma$, where $M$ is any integer ; this expression is independent of $q$. If, on the other hand, we deal with the total angle $\theta$ between the first and last vectors, for the resultant to have the same numerical value the displacement must be $q \, . \, 2M\pi \pm \theta$, a value which increases directly with $q$. Thus the distribution factor corresponding to the $m$th harmonic may be stated in the form utilized by the authors, viz. $(\sin m\sigma/2) \div (q \sin m\sigma/2q)$. Alternatively it may be expressed in the form $(\sin qm\gamma)/(q \sin m\gamma)$. The former expression when plotted as a function of $m\sigma$ gives a graph which, numerically, is periodic with range $2q\pi$. The latter when plotted as a function of $2m\gamma$ gives a graph which for all values of $q$ is periodic, numerically, with range $2\pi$. It thus appears that the best method of tabulating these factors is as functions, not of $\sigma$ or $m\sigma$, but of the equivalent slot-pitch $2m\gamma$, i.e. of the slot-pitch expressed in electrical measure to correspond to the particular harmonic under investigation. Similarly, it would appear that the best method of plotting out the factors is in terms of the equivalent slot-pitch above mentioned. It then becomes possible, on the same base from 0° to 180°, to plot graphs representing the factors for various values of $q$, e.g. 2, 3, 4, 5, 6, 8 and 10. From these seven graphs the values of the factors corresponding to any harmonic can at once be read off, for any value of the equivalent slot-pitch. With this common base it is easily possible to deal with angles above 180°, i.e. values of $2m\gamma$ greater than $\pi$. All that is necessary is to number each main ordinate with the values of the first four angles to which it corresponds. Thus the 10° ordinate is numbered 10°, 350°, 370°, 710°, etc., the 20° ordinate 20°, 340°, 380° and 700°, etc. It is extremely unlikely that any harmonic for which the equivalent slot-pitch much exceeds 720° will require investigation, as this figure corresponds very closely to the value obtaining for the tooth-ripple harmonics of the second order. The sign of the factor, although often of little importance, is also very simply obtained. When $q$ is an odd number, the sign is always as given by the graph ; when $q$ is even, the sign as given by the graph must be reversed for angles lying between 180° and 540°, and, of course, between 900° and 1 080°, etc. The first limits include certainly all the cases that need to be considered, in this respect, in practice.

In a paper on " A Mathematical Development of the Theory of the Magnetomotive Force of Windings," * I have given tables showing the value of the distribution factor for values of the equivalent slot-pitch, $2m\gamma(180°/\pi)$, from 0°, in steps of 2°, to 180°, and for $q = 2$, 3, 4, 5, 6, 8, 10 and 12. These tables cover all the numerical values of the factor for the given values of $q$. I have also represented the values of the factor in the form of a simple family of graphs on the lines mentioned above. A single graph serves for harmonics of every order for one particular value of $q$. Thus, for example, with $q = 3$ the distribution factors are read off from a graph representing $\sin \frac{1}{2}(3\theta)/3 \sin \frac{1}{2}\theta$ plotted from $\theta = 0°$ to $\theta = 180°$, the ordinates being numbered as indicated above. If, for example, the slot-pitch were 14°, corresponding to an unusual slotting, the factor for the fundamental is read off at 14°, for the second at 28°, for the third harmonic at 42°, . . . the 21st at 294°, etc. For $q = 4$ and the same slot-pitch the values of the factor would be read off from a graph representing $\sin \frac{1}{2}(4\theta)/4 \sin \frac{1}{2}\theta$, and it would be necessary to reverse the sign of the factors read off between 180° and 540°. For values of $q$ greater than 12, the winding factors for the lower harmonics approach so closely those for a corresponding surface winding that, in common with the authors, I have found it convenient to utilize the graph representing $\sin \frac{1}{2}\theta/\frac{1}{2}\theta$. For the higher harmonics it is sufficient to remember that when $S$, the number of slots per pair of poles, is an integer, the distribution factors for harmonics of orders $MS \pm m$ all have the same numerical value as for the $m$th harmonic. It is desirable, however, to be able to obtain accurately and simply the values of the factors in certain cases. The error of 28 parts in 77 quoted by the authors may occasionally be of moment, although it occurs in a relatively small term. The correct value of the factor can readily be deduced from the above graph, for

---

* Paper by Messrs. B. Hague and S. Neville (see vol. 60, page 861).

† *Journal I.E.E.*, 1915, vol. 53, p. 205.

‡ *Electrician*, 1917, vol. 78, pp. 710, 740 and 765.

* To be published in a later number of the *Journal*.

$$\frac{\sin qm\gamma}{q \sin m\gamma} = \frac{\sin qm\gamma}{qm\gamma} \cdot \frac{qm\gamma}{q \sin m\gamma}$$
$$= \frac{\sin \frac{1}{2}m\sigma}{\frac{1}{2}m\sigma} \div \frac{\sin m\gamma}{m\gamma}$$

Hence, to obtain the correct value it is only necessary to divide the factor obtaining for a surface winding of spread $m\sigma$ by that obtaining for a spread of $2m\gamma$, i.e. a spread of the equivalent slot-pitch.

For example, with $q = 12$, and 18 slots per pole, the equivalent slot-pitch for the 17th harmonic is 170°, and the equivalent spread of the phase group is 17 × 120° = 2 040°. The factors corresponding to these spreads are, respectively, 0·672 and − 0·049. Hence the actual distribution factor is − 0·049/0·672, i.e. − 0·073, instead of the value − 0·049 which obtains for the corresponding surface winding.

**Messrs. B. Hague** and **S. Neville** (*in reply*): Though the authors think it doubtful whether the results are simpler when expressed in terms of the slot-pitch instead of the phase-spread, yet they welcome the attention which Mr. Clayton has drawn to the former method of representation. The general form of the curves remains, of course, unchanged; and although the complete period is reduced from $2q\pi$ to $2\pi$ in all cases, the curves make $q$ oscillations about the axis in that period. In tabulation, apparently there would be little to choose between the two methods; and in plotted curves it becomes a question of whether a longer base-line or a curve crossing the axis at frequent intervals is to be considered the more convenient. From the purely mathematical point of view, it is to be noted that each of the forms in which the distribution can be expressed, namely $(\sin m\sigma/2)/(q \sin m\sigma/2q)$ and $(\sin qm\gamma)/(q \sin m\gamma)$, has its own particular merit; both forms have been used in the papers cited above by Mr. Clayton.

For practical purposes the method adopted in the paper may be preferred. In the alternative method, the curves for different values of $q$ cross and recross each other in a rather bewildering manner; the curves do not remain distinct (as in Fig. 4, for instance), on account of the very different shapes of the several curves. The confusion is greatly increased by each further value of $q$ that is shown. The arrangement of Fig. 3 avoids this difficulty, and shows clearly the change introduced into the curve by each successive increase of $q$. Mr. Clayton proposes, for practical use, to omit curves for $q$ greater than 12. It is then impossible to find the factor for, say, $q = 13$ or 14 from the set of curves, while in Fig. 3 any higher value of $q$ can be directly dealt with, accurately if $\alpha$ is not greater than $6\pi$, and to a fair approximation for any greater angles, by comparison with the curve for $q = \infty$. This last and important curve cannot be combined with others plotted to a base of slot-pitch.

The authors wish to express their great indebtedness to Mr. Clayton for his simple formula for deriving the distribution factor for any slotting from the curve for a uniformly-distributed or surface winding. Expressed in the notation of the paper, Mr. Clayton's formula becomes

$$f_q(\theta) = f'(\theta) \div f'(\theta/q)$$

that is, the distribution factor for $q$ vectors spread over a total arc of $2\theta$ is equal to that of an infinite number of vectors occupying the same total arc divided by that of an infinite number of vectors occupying the space between any pair of the actual vectors. By this simple operation the range of Fig. 3 is extended indefinitely and without approximation, thus covering the only region for which accurate values are not directly indicated in the curves reproduced. Applying the rule to the example mentioned in the footnote on page 864, from the curve in Fig. 3 the distribution factor at $\alpha/q$ (that is, $\pi/2$) is found to be 0·635; the value at $\alpha$ (that is, $13\pi/2$) is 0·049; so that the correct value for $q = 13$ is 0·049/0·635 = 0·077.

# ANNUAL DINNER, 1923.

The Annual Dinner of the Institution was held on Tuesday, 6th February, 1923, at the Hotel Cecil

The President, Mr Frank Gill, presided over a gathering numbering about 480 persons. Among those present were: The Rt. Hon. Neville Chamberlain, M.P. (*Postmaster-General*), Sir W. Joynson-Hicks, Bart., M.P. (*Parliamentary Secretary, Overseas Trade Department*), The Rt. Hon. Lord Southborough, P.C., G.C.B., G.C.M.G., G.C.V.O. (*Honorary Member*), The Rt. Hon. Lord Askwith, K.C.B. (*Chairman of Council, Royal Society of Arts*), The Rt. Rev. Bishop H. E. Ryle, K.C.V.O. (*Dean of Westminster*), Sir Anthony Bowlby, K.C.B., K.C.M.G., K.C.V.O. (*President, Royal College of Surgeons*), Sir S. Chapman, K.C.B., C.B.E. (*Permanent Secretary, Board of Trade*), Sir R. T. Glazebrook, K C.B., F.R.S. (*Past President*), Sir Frank Heath, K.C.B. (*Secretary, Department of Scientific and Industrial Research*), Sir Evelyn Murray, K.C.B. (*Secretary, General Post Office*), The Hon. Sir T. H. Holland, K.C.S.I., K.C.I.E., F.R.S. (*Rector, Imperial College of Science and Technology*), Sir John Cadman, K.C.M.G., D.Sc. (*President, Institution of Mining Engineers*), Major-Gen. Sir William Liddell, K.C.M.G., C.B., late R.E. (*Director of Fortifications and Works, War Office*), Sir Westcott Abell, K.B.E. (*Chief Ship Surveyor, Lloyd's Register of Shipping*), Sir Arthur Colefax, K.B.E., K.C., Sir James Devonshire, K.B.E. (*Honorary Treasurer*), Sir William Hale-White, K.B.E., M.D. (*President, Royal Society of Medicine*), Sir Joseph Petavel, K.B.E., D.Sc., F.R.S. (*Director, National Physical Laboratory*), Sir Robert Robertson, K.B.E. (*President, Faraday Society*), Sir A. I. Durrant, C.B.E., M.V.O. (*H.M. Office of Works*), Sir William Noble (*Member of Council*), C. T. Allan (*Joint Hon. Secretary, Western Centre*), Ll. B. Atkinson (*Past President*), F. G. C. Baldwin (*Chairman, North-Eastern Centre*), W. N. Bancroft (*President, Chartered Institute of Secretaries*), J. W. Beauchamp (*Member of Council*), W. E. Burnand (*Past Chairman, North Midland Centre*), Alfred Carpmael, A. C. Chapman, F.R.S. (*President, Institute of Chemistry*), R. A. Chattock (*Member of Council*), F. W. Crawter (*Member of Council*), R. A. Dalzell, C.B.E. (*Director of Posts and Telephones, General Post Office*), W. R. Davies, C.B. (*Principal Asst. Secretary, Technical Branch, Board of Education*), D. N. Dunlop (*Member of Council*), Dr. W. H. Eccles, F.R.S. (*Vice-President*), K. Edgcumbe (*Member of Council*), A. S. Hampton (*Chairman, Scottish Centre*), A. F. Harmer (*Member of Council*), Dr. H. S. Hele-Shaw, LL.D., F.R.S. (*President, Institution of Mechanical Engineers*), J. S. Highfield (*Past President*), Captain H. Hooper (*Hon. Secretary, South Midland Centre*), G. W. Humphreys, C.B.E. (*Chief Engineer, London County Council*), Dr. R. Knox (*President, Electrotherapeutic Section of Royal Society of Medicine*), Lieut.-Col. F. A. C. Leigh, T.D., R.E. (*Member of Council*), W. M. Mordey (*Past President*), A. Page (*Member of Council*), C. C. Paterson, O.B.E. (*Vice-President*), A. C. Peake (*President, Incorporated Law Society*), Major T. F. Purves, O.B.E. (*Engineer-in-Chief, General Post Office*), Councillor E. C. Ransome (*President, British Electrical Development Association*), W. R. Rawlings (*Member of Council*), P. F. Rowell (*Secretary*), Dr. A. Russell (*Member of Council I.E.E., and President, Physical Society of London*), A. M. Sillar (*Chairman, Association of Consulting Engineers*), Roger T. Smith (*Past President*), C. P. Sparks, C.B.E. (*Past President*), S. J. Speak (*President, Institution of Mining and Metallurgy*), A. A. C. Swinton, F.R.S. (*Vice-President*), H. L. Symonds (*Chairman of Council, London Chamber of Commerce*), F. Tremain (*Chairman, Western Centre*), C. Vernier (*Member of Council*), E. B. Vignoles (*Chairman, British Electrical and Allied Industries Research Association*), C. H. Wordingham, C.B.E. (*Past President*).

After the usual loyal toasts, the President read the following message:

"His Royal Highness the Prince of Wales had hoped till the last moment to be able to give his favourable consideration to the President and Council's invitation to be present at the Annual Dinner of the Institution, but the overwhelming number of invitations which he has received for 1923 (the majority of which are of long-standing, having accumulated during his various absences overseas) has rendered the drafting of his programme for this year of unusual difficulty. The Prince fears that as a result he will be unable to accept the Institution's kind invitation for 1923, though there is of course nothing to prevent the Council, should they so desire, from renewing it on some future occasion when His Royal Highness is in England."

The President also read the following messages which had veen received from other societies:

*From French Society of Electricians.*

"The French Society of Electricians sends most cordial greetings to the President and members of the Institution of Electrical Engineers on the occasion of the Annual Dinner. The Society strongly desires the continuance of the most friendly relations between the two bodies and the two nations."—BRILLOUIN, *President.*

*From Italian Electrotechnical Association.*

"The Italian Electrotechnical Association fully appreciate your kind thought and would ask you to present to their English colleagues the hearty wishes and greetings of Italian electrical engineers. Personally I send you and your Institution my wishes for a happy year and prosperity."—DEL BUONO, *General President.*

*From American Institute of Electrical Engineers.*

"Please convey to President Gill members of Council and of Institution of Electrical Engineers on occasion their Annual Banquet hearty felicitations from officers and members of the American Institute of Electrical Engineers."—F. B. JEWETT, *President.*

**Sir W. Joynson-Hicks, Bart., D.L., M.P.** (Parliamentary Secretary, Overseas Trade Department), in proposing the toast of "The Institution of Electrical Engineers," said: In proposing this toast, coupled with the name of your President, I should like to congratulate him on his accession to this high and distinguished position. I am certain that he will fill it in accordance with the great tradition of the past, and that he will be a worthy successor to those great men, such as Siemens, Crookes, Preece, and Glazebrook, who have been your Presidents in times past. Your Institution is one of the marvels of modern days. Beginning some 50 years ago with a very few members, it is now the largest scientific Institution in the British Empire, with a membership of nearly 11 000—a great record and a great Institution. I suppose the reason why the Institution has become so important is partly because of the importance of the electrical agencies and of the electrical profession, and also because of its fundamental principle, which, I understand, is that of advancing knowledge and improving practice—a motto which most Government Departments might well take for their own. May I say that, in carrying out your principle, you might combine with the Government institutions—you doing the research part, and, at all events, the Department over which I have the honour to preside doing the commercial part. I presume that it is because of my official position that I have been asked to propose to-night the health of your Institution, the development of which would assist very greatly in the development of our overseas trade. I want to see research and commerce combined. I am convinced that the commercial man who sneers at research, and who is not prepared to lay out the necessary funds for the development of the industry with which he is connected, is far behind the times and is a hindrance to the progress of commerce in this country and to the development of overseas trade. On the other hand, the pure scientist sometimes works merely for the sake of working, and for the pleasure of investigating the unknown, very often not knowing when he is done. I may say that to-night I have asked, with an inquiring mind, of two of the greatest authorities on the subject, "What is electricity?" and both those scientists have replied that they do not know. But it is by the development of science by the pure scientist, yoked in double harness with the commercial man, that the trade of our country has developed in the past and will develop in the future. I should like to comment on one project which I notice in your Council's last Annual Report, that is, the development of the system of instruction given to overseas students coming here into our factories, our workshops and our training colleges. Remember this—that every student from abroad who comes here, who learns here, and who is well treated here, when he goes back to his own country is worth any ten commercial travellers in the world. He goes back with the determination in his mind that English science, English trade and English manufacture are better than any other science, trade and manufacture in the world. When he gets back to his own country, we may be certain that he will spread abroad the knowledge of English science and English manufacture better than any other agency which the scientists or the manufacturers in this country could devise. I want therefore to see this system very much enlarged and very much encouraged, and if my Department's agencies overseas and its staff here can be of any assistance in bringing together would-be students from overseas and the factories here, we are absolutely at your disposal. May I ask you one more thing? As one who has some knowledge now of our export trade, I say that it is of the very greatest importance that you should continue to standardize in every possible way your electrical specifications so that all the world may realize what those specifications mean, and so that, when the world sees an English specification, it will know it to be one of the best. Whatever difficulties there may be in the trade of the future, whether they are from tariffs or from any other cause, I assure you that quality, for which in the past Great Britain has been famous, will overcome all tariffs and all other obstacles to trade throughout the world. In every country there is always a market for the best. England has always been proud of providing the best. Your Institution has striven in the electrical industry to be of assistance in providing the best. Great as has been your past, great as have been the achievements in electrical science, that is nothing compared with the possibilities of the future. The prospects to-day are even more brilliant than they were 50 years ago. There is no man, however keen a scientist he may be, sitting at this table who would venture to set a limit to the possibilities of the extension of the electrical industry and of electrical discovery. It may be that in another 50 years' time, when some other Ministry of the Crown comes to propose this toast at an enormously enlarged gathering, somebody may be able to answer that question which I asked a few minutes ago. But if it cannot even then be answered, you and I are convinced that although you may not be able to define it in so many words you will define it by the progress of your Institution and by the progress and development of electrical Institutions throughout the world. I give you, with very great pleasure, the toast of "The Institution of Electrical Engineers," coupled with the name of your President, to whom I wish long life and prosperity.

**The President,** in responding, said: "I have to thank Sir William Joynson-Hicks very cordially for the way in which he has spoken of the Institution, and I am sure that the words which he has used have fallen very gratefully on the ears of those who are enthusiastic about the Institution. To-night I want to talk about three important things. The Report for the year ending March 1922, lately issued by the Electricity Commission, shows that from 536 generating stations the total output for 1921–22 decreased by 5½ per cent. Of those stations, no less than 43 per cent had an output of under one million units per annum. The estimates for eight areas provisionally delimited by the Commissioners show that during the next five years the increase in output will be of the order of 97 per cent, and for ten years about 192 per cent. The published figures, so far as I have seen them, suggest that the estimates will be exceeded. That seems to me to be very hopeful. The reason I mention this is that in this country, owing to reasons into which it is unnecessary for me to go, we have a considerable number of small undertakings and, although I am not a power engineer, I am sure that the generation business of those small undertakings cannot in many cases be economical. Now, when we consider some of the large undertakings which are at present in operation in Switzerland, on our North-East Coast, in the United States, and in Canada, we can only hope that we shall find in this country a tendency to merge and unify the generation of electricity. Let me give an illustration. Last summer, at Niagara, I went over the Ontario Power Commission's works. The Commission was then supplying 275 municipalities. Its load was equal to about 340 000 h.p. The 1920 price for energy for commercial purposes varied from 1·3 to 5 cents per kilowatt-hour, and for domestic purposes the price varied from 2·2 to 4 cents per kilowatt-hour. Its big power station on the Niagara River was being built with an ultimate capacity of 500,000 h.p. I want to conclude my remarks on this matter with a plea that those who have to deal with these problems in this country will do their best to merge their interests, to amalgamate as far as they can, and to build up big businesses, because it is only big businesses that can be strong. The second big thing I want to refer to is international telephony in Europe. At the first meeting of the Institution this session reference was made to this matter. It was shown that there is no longer any technical difficulty in speaking overland over any distance that may be desired. Since then, on 15th January, it was proved that it was quite possible to speak over long distances over sea. It was shown at our opening meeting that there are working in the world telephone lines in everyday use which appear very long to European eyes—much longer than those we have in practice. I think it is fair to say that no Government in Europe—this is largely a question for Governments—dare take an order for an international telephone call on a contractual basis. It will take the order and do its best, but it dare not take it on a contractual basis because no Government has the control which is necessary. I think it was shown, also, that a first-class extensive telephone service in Europe is not possible under the present conditions. This is no one's fault. The necessary technical advances have only recently been achieved which enable this to be contemplated. At the present time it is no one's job. Since November some progress has been made because the French Government has issued invitations for a meeting, which will probably be held next month, to consider this matter and see what can be done. This is not a matter for co-ordination. It is not a matter for a book of rules. There is only one way to tackle it and that is to deal with it boldly by arranging for unity of control for the whole of the through-business. Sir William has referred to the question of research. I should like to quote from a speech made by Mr. Theodore N. Vail—probably the man who was responsible for more expenditure on research than any other individual in the world's history. Mr. Vail said : " Given the ideas and the knowledge and the brains, development in any line of art, science or industry is largely a question of money." That is very true. Research is costly in the first instance, but it is very profitable in the end. It is, however, becoming more and more a question of organization and team work. I think it is only the big concerns which can afford to spend the money necessary to bring research to successful fruition. That is why I couple these two big things with research. The third big thing I want to mention is the Institution. The membership is now 10 600. During the last four years it has increased by over 3 000. That is at the rate of 9 per cent per annum, a rate which doubles the total in 8 years. The Students' Sections are in a highly flourishing condition. They never were better, and I am glad to say that among those Students are many of those whom Sir William has in mind. There are at present 12 Local Centres or Sub-Centres holding their meetings away from London, and in those Local Centres and Sub-Centres there are 4 700 members, nearly 45 per cent of the whole membership. That is to say, the Institution is able to cater for 45 per cent of its membership away from London. One of those Sub-Centres, Liverpool, has just been granted the status of a Local Centre, with the consent and approval of its late parent Centre. In those Centres splendid work is being and has been done, and I should not like to sit down without expressing the thanks of the Council to the Committees and the Local Officers of those Centres. At the same time I should also like to thank the headquarters staff and particularly the Secretary, Mr. Rowell. I want now to refer to one of the offshoots of the Institution. Twenty-five years ago the late Dr. John Hopkinson, then President, started the Corps of London Electrical Engineers. That body has now been, shall I say, re-galvanized after a period of calm, and it now emerges as the 11th Anti-Aircraft Battalion. Lieut.-Col. Edgcumbe wants recruits and will be very glad of anyone who will come forward. The Headquarters are still at Regency-street, Westminster.

" I have talked about the Institution, but I do not desire to see you occupied solely with the Institution. That would be class interest. The smallest unit that ought to satisfy the members is the nation. We are only part of a body of men who are doing similar or analagous work to ours ; the representatives of some of those other societies have honoured us by their presence to-night. To those other societies we are brothers, not rivals. We feel with them the same desire to do service, and we reach forward with them to do our utmost to minister to human needs, and, by applying the gifts which science gives, to do something to render mankind more useful, more happy and more contented. I thank you for the way in which this toast has been received."

**Mr. J. S. Highfield**, Past President, then proposed the toast of " Our Guests," to which the **Rt. Hon. Neville Chamberlain, M.P.**( Postmaster-General), and **Sir Arthur Colefax, K.B.E., K.C.**, responded.

A reunion was then held in the Victoria Hall of the Hotel.

# PROCEEDINGS OF THE INSTITUTION.

## 688TH ORDINARY MEETING, 30 NOVEMBER, 1922.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 16th November, 1922, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read, and was ordered to be suspended in the Hall.

The following list of donations was taken as read, and the thanks of the meeting were accorded to the donors:—

*Museum :* The Lords Commissioners of the Admiralty; The Delegacy of the City and Guilds (Engineering) College; The Engineer-in-Chief, G.P.O.; The Committee of the Liverpool Public Libraries; Professor T. Mather, F.R.S.; C. Owen Silvers; The Elder Brethren, Trinity House.

A paper by Mr. W. A. Gillott, Associate Member, entitled "Domestic Load Building: a Few Suggestions upon Propaganda Work" (see page 197), was read and discussed, and the meeting terminated at 8 p.m.

## 25TH MEETING OF THE WIRELESS SECTION, 6 DECEMBER, 1922.

(Held in the Institution Lecture Theatre.)

**Mr. E. H. Shaughnessy, O.B.E.,** took the chair at 6 p.m. in the unavoidable absence of Professor G. W. O. Howe, Chairman of the Section.

The minutes of the meeting of the Wireless Section held on the 8th November, 1922, were taken as read and were confirmed and signed.

A paper by Mr. E. B. Moullin, M.A., entitled "A Direct-reading Thermionic Voltmeter, and Its Applications" (see page 295), was read and discussed, and the meeting terminated at 7.20 p.m.

## 689TH ORDINARY MEETING, 7 DECEMBER, 1922.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 30th November, 1922, were taken as read and were confirmed and signed.

**The President :** Before we begin the regular business it is my pleasant duty to present to you our latest Honorary Member, Dr. Fleming.

**Dr. J. A. Fleming :** I should like to express my deep sense of the honour which the Institution has done me by placing my name on its list of Honorary Members. It is a very high distinction, and one which I value and appreciate very much indeed. I have been a Member of this Institution now for rather more than 40 years, having been elected in the spring of 1882, when I first came to London as a scientific adviser to the old Edison Electric Lighting Company. Looking back on those 40 years I see a wonderful vista of inventions, in the origination and development of which members of this Institution have played a most important part. In those days the name of the Institution was the Society of Telegraph Engineers and Electricians, and there was no "heavy" electrical engineering in the sense in which we now understand the term. The incandescent lamp had only just been invented by Edison and Swan. Dynamo machines in those days were considered rather wonderful if they could run for 24 hours without breaking down. Transformers and alternators had hardly been invented at all, and all our modern appliances, such as wireless telegraphy, were undreamed of. In looking back on that period one sees the first developments of electrical engineering, and I feel confident that in another equal span of time other wonderful inventions will be evolved. Let us hope that if our statesmen and politicians can steer the ship of State into smooth waters, and those conditions return which will give a proper financial reward to all electrical engineers in return for the great benefits which they bestow upon the community, these things will come to pass. It is a distinction to belong to this Institution in any form or in any rank, and it is a very great distinction to be numbered among its Honorary Members.

A paper by Mr. A. M. Taylor, Member, entitled "The Possibilities of Transmission by Underground Cables at 100 000/150 000 Volts" (see page 220), was read and discussed, and the meeting terminated at 8 p.m.

## 690TH ORDINARY MEETING, 14 DECEMBER, 1922.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 7th December, 1922, were taken as read and were confirmed and signed.

**The President:** There is a purely formal matter in connection with the Wilde Benevolent Fund which I wish to put to the members. The Council have taken steps for the transfer to the members of the chartered Institution of the benefits under the Wilde Benevolent Fund which accrued to the members of the old Institution. For certain legal reasons the transfer will have to be effected by means of an application to the High Court. As it is possible that the learned judge may ask whether there is a sufficient number in favour of the transfer being effected (there has to be no particular number of members) it was thought wise to ask whether anybody present has any objection. The point is purely formal. I take it that you agree to this course being followed. [The members present unanimously signified their assent.]

A paper by Major J. Caldwell, entitled "Electric Arc Welding Apparatus and Equipment" (see page 253), was read and discussed, and the meeting terminated at 7.45 p.m.

## 691ST ORDINARY MEETING, 4 JANUARY, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The following vote of condolence with the family of the late Sir John Gavey, C.B., Past President, was passed, the members standing in silence :—

> "The members of the Institution of Electrical Engineers have learned with profound regret of the death of Sir John Gavey, C.B., Past President of the Institution, and hereby desire to express their sincere sympathy with the members of his family in the great loss which they have sustained through his death."

The minutes of the Ordinary Meeting of the 14th December, 1922, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Mr. F. Creedy, Associate Member, then delivered a lecture entitled "Variable-speed Alternating-current Motors without Commutators" (see page 309), and the lecture was followed by a discussion (see page 326).

The meeting terminated at 8.5 p.m.

## 26TH MEETING OF THE WIRELESS SECTION, 10 JANUARY, 1923.

(Held in the Institution Lecture Theatre.)

**Prof. G. W. O. Howe, D.Sc.,** Chairman, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 6th December, 1922, were taken as read and were confirmed and signed.

A paper by Mr. C. F. Elwell, Member, entitled "The Design of Radio Towers and Masts: Wind-Pressure Assumptions" (see page 407), was read and discussed, and the meeting terminated at 7.15 p.m.

# STATIONARY WAVES ON OPEN-ENDED SOLENOIDS.[*]

By A. PRESS, Member.

(*Paper first received* 6*th December*, 1921, *and in final form* 11*th April*, 1922.)

The problem of the coupling coil has received new importance physically because of its application to wireless signalling. The nodal-point distribution on an elongated Tesla coil has been recently investigated, and it was found that the nodal distances fell off in value as the ends of the coil were approached.[†]

This attenuation of distance had been attributed to end-effects, but it will be shown in this paper that the cause is rather a body effect. Naturally, with the maximum self-induction and capacity per unit of length occurring at the middle of the coil, the results must be of altogether different character from those obtaining in a Bessel's antenna,[‡] where the capacity per unit of length diminishes as the self-induction coefficient increases. The same would be equally true against the Bessel's cable of Oliver Heaviside,[§] although the general differential characteristics still apply.

For the present case assume the following relationship for a coil with the co-ordinate $x$ measured from the centre outward.

$$\left.\begin{aligned} L_x &= \frac{L}{\phi(x)} \\ C_x &= \frac{C}{\phi(x)} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

In the above equations $L_x$ and $C_x$ diminish together towards the ends of the coil, the arbitrary function $\phi(x)$ depending on the geometry of the coil only. In the Maxwellian theory the capacity per unit of length is to be determined from the direct-current condition only with one-half of the coil charged plus and the other half minus. This method has always been implied in dealing with waves along wires (see, notably, the work of Heaviside [‖]).

The differential equations of condition, neglecting resistance, being of the form [‖]

$$\left.\begin{aligned} L_x \frac{di}{dt} &= -\frac{de}{dx} \\ C_x \frac{de}{dt} &= -\frac{di}{dx} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (2)$$

On separating out the voltage and current functions we have

$$\left.\begin{aligned} \frac{d^2e}{dx^2} + L_x \frac{d}{dx}\left(\frac{1}{L_x}\right) \cdot \frac{de}{dx} &= L_xC_x \frac{d^2e}{dt^2} \\ \frac{d^2i}{dx^2} + C_x \frac{d}{dx}\left(\frac{1}{C_x}\right) \cdot \frac{di}{dx} &= L_xC_x \frac{d^2i}{dt^2} \end{aligned}\right\} \quad . \quad . \quad (3)$$

The above equations bear a considerable resemblance to Bessel's equation. If then we make use of equation (1) it follows that for sustained oscillations of frequency $f = (1/2\pi)p$, Equation (3) reduces to

$$\frac{d^2e}{dx^2} + \frac{1}{\phi(x)} \cdot \frac{d}{dx}\,\phi(x) \cdot \frac{de}{dx} + \frac{LCp^2}{(\phi x)^2}\,e = 0 \quad . \quad . \quad (4)$$

with a similar equation in $i$.

The solution of Equation (4) has been determined by the author to be of the form

$$e = [A \sin f(x) + B \cos f(x)] \sin pt \quad . \quad . \quad (5)$$

where we also have as conditions first that

$$\frac{d}{dx} f(x) = \frac{1}{\phi(x)} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and secondly, that

$$f = \frac{1}{2\pi\sqrt{(LC)}} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Provided, therefore, that any function such as $\phi(x)$ is known, the corresponding solution (5) is also known.

By inspection it follows from Equation (5) that the nodal distances of potential and current should progressively diminish toward the free end of the coil. Condition (7) implies that, provided the distributed inductance and capacitance accord with Equations (1), very sharp resonance will result.

To check the above type of solution (5) consider

$$e = A \sin f(x) + B \cos f(x)$$

then $\quad de/dx = A \cos f(x) \, . \, f'x - B \sin f(x) \, . \, f'x$

and $\quad (1/f'x)de/dx = A \cos f(x) - B \sin f(x)$

Operating once more with $d/dx$ we have

$$\frac{1}{f'x} \cdot \frac{d^2e}{dx^2} + \frac{d}{dx}\left(\frac{1}{f'x}\right) \cdot \frac{de}{dx}$$
$$= -A \sin f(x) \, . \, f'x - B \cos f(x) \, . \, f'x = -f'x \, . \, e$$

from which we have, on multiplying through by $f'x$,

$$\frac{d^2e}{dx^2} + (f'x)\frac{d}{dx}\left(\frac{1}{f'x}\right) \cdot \frac{de}{dx} + (f'x)^2e = 0$$

---

[*] The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] Prof. J. S. TOWNSEND: "Electric Oscillations in Straight Wires and Solenoids," *Journal I.E.E.*, 1921, vol. 59, p. 771; also *Philosophical Magazine*, 1920, vol. 42, p. 248.

[‡] A. PRESS: "The Vertical Grounded Antenna as a Generalized Bessel's Antenna," *Proceedings of the Institute of Radio Engineers*, 1918, vol. 6, p. 317.

[§] O. HEAVISIDE: "Electromagnetic Theory," vol. 2, p. 238.

[‖] *Loc. cit.*, p. 239, Equations (1) and (2).

This therefore necessitates, according to the first equation of (3),

$$f'x = L_x;\ (f'x)^2 = L_x C_x p^2$$

Writing therefore

$L_x = d/dx(fx) = L/\phi(x)$ (where $L$ is a constant),

$C_x = C/\phi(x)$ (where $C$ is a constant),

we have $L_x C_x = LC/(\phi x)^2$; $L_x C_x p^2 = 1/(\phi x)^2$

provided we put $LCp^2 = 1$, which gives $p = 1/\sqrt{(LC)}$.

Equation (5) may be said to give the "resonant" solution. The "dissonant" solution is given by an expression of the type

$$e = A\sum\frac{1}{n^2} . \sin nf(x) . \sin pt \quad . \quad . \quad . \qquad (8)$$

which applies more particularly for the case of dead-ends which naturally give rise to out-of-phase reflection phenomena. The latter circumstance has important practical consequences for wireless work where the sharpest type of resonance is a desideratum.

In passing, dealing with the subject of the self-induction coefficient of a coil, it has been held recently that the coefficient is a function of the frequency. There is no evidence of this in Heaviside's "Electromagnetic Theory." Thus in considering a closed circuit we have the expression, neglecting resistance, that

$$n\frac{d\phi}{dt} = e \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (9)$$

where $e$ is the impressed E.M.F. and $\phi$ represents the aggregate flux linking the circuit, on the basis of $n$ effective turns. Turning now to the case of a very long transmission line [where capacities are naturally present and we have the formula $C = 1/(Lc^2)$, where $c$ is the velocity of light] with a frequency of practically zero value, it is endeavoured to put Equation (9) into the form

$$n\frac{d\phi}{dt} = L\frac{di}{dt} = e \quad . \quad . \quad . \quad . \qquad (10)$$

Here $L$ is presumed to refer to the conductive length of the circuit only. Each elemental length $ds$ of the conductive portion is presumed to add its quota of flux linkages that physically cut the circuit forming the conductor, in accordance with the Faraday requirement. Having thus allocated a definite flux-cutting value to each portion of the conductive part of the circuit for the same current intensity $i$ passing through it, it is further held that for the case of high frequencies, where the current intensity may be varied, the voltage set up per element of length $ds$ is still of the form

$$de = (Lds)di/dt \quad . \quad . \quad . \quad . \qquad (11)$$

All the older writers have employed the above theory in their investigations of stationary waves on wires. The method applies, of course, to the electrical configuration coefficient $C$ as well as to the magnetic configuration constant $L$.

# THE DESIGN OF RADIO TOWERS AND MASTS: WIND-PRESSURE ASSUMPTIONS.

By C. F. Elwell, Member.

(*Paper first received 30th November, and in final form 7th December, 1922; read before the* Wireless Section *10th January, 1923.*)

## Summary.

In all theory, design and specifications, some assumptions are necessary and, as experience is gained, the value and accuracy of these assumptions is made apparent. The ultimate weight and cost of a structure is influenced in no small degree by the initial considerations, and in the particular field under review the question of maximum wind pressures and the law connecting such pressures with height above ground level, are of primary importance. It is the intention of this paper to review briefly the results of past experiments and endeavour to point out what are safe and economic values of wind pressures for design purposes. The need for the standardization of wind-pressure assumptions will also be brought out and it is sincerely hoped that practical action will be taken in the near future.

## Newton's Theory for Fluids.

The general theoretical treatment extends from the time of Galileo (1590) and was put into practical form by Newton in his "Principia" about 1687 in terms which are expressed to-day by the general formula *

$$p = da\,H = da\frac{v^2}{2g}$$

where $p =$ pressure on the body;
$a =$ area of body;
$d =$ density of fluid;
$v =$ velocity of fluid relative to the plate; and
$H = v^2/2g =$ height required for a body to attain a velocity $v$ under the action of gravity.

This formula modified to apply particularly to air becomes

$$p = \frac{0\cdot0027}{1 + 0\cdot003665t} \cdot \frac{P}{P_1}v^2$$

where $p =$ pressure in lb. per sq. ft. of exposed area;
$t =$ temperature in degrees C.;
$P =$ barometric pressure at place of observation;
$P_1 =$ barometric pressure at sea level at the 45th parallel of latitude and at 0° C.; and
$v =$ velocity of fluid in miles per hour.

At zero temperature and sea-level barometric pressure at the 45th parallel this formula reduces to:

$$p = K \times 0\cdot0027v^2$$
$$= K \times \frac{1}{370} \times v^2$$

In this formula $K$ (equal to 1 in this case) is a constant introduced for the comparison of Newton's theoretical formula with the later formulæ of practice and experiment.

All investigators have sought to prove the formula or to find the extent of the discrepancy, and have found that $K$ varies between 1·3 and 1·8, the gain being ascribed particularly to the partial vacuum in the rear of the plates. In these investigations some have added constants to allow for this, while others have added terms to express variations in the higher powers of $v$, producing formulæ of the general form

$$p = A + Bv + Cv^2 + Dv^3$$

*Examples of formulæ.*—Stevenson* gave

$$V = v\sqrt{\left(\frac{H + 72}{h + 72}\right)}$$

where $V =$ velocity at level $H$; and
$h =$ known height at which the velocity is $v$.

E. Douglas Archibald † found, from observations between 300 and 1 300 ft.,

$$\frac{V}{v} = \left(\frac{H}{h}\right)^{\frac{1}{4}}$$

where $V$, $v$, $H$, and $h$ are the velocities and heights of the upper and lower instruments respectively. He says "the general and obvious conclusion to be drawn . . . is that the velocity of the wind *always* increases from the surface of the ground up to 1 800 ft. . . ."

Sir Napier Shaw gives‡

$$V = \frac{H + a}{a} \cdot V_0$$

where $V =$ velocity at a height $H$ above ground;
$V_0 =$ observed anemometer reading in a fixed position; and
$a =$ a constant obviously depending on the position of the anemometer, topography and other factors.

In general it has been found that near the earth the actual velocity is exceedingly irregular, but that the *average velocity* increases with height. The rate of increase *increases* with the average velocity, and *decreases* with the elevation.

---

* *Engineering News Record*, 1895, vol. 35, p. 175.

* *Journal of the Scottish Meteorological Society*, 1880, vol. 5 p. 384.

† *Nature*, 1886, vol. 33, p. 593.

‡ Advisory Committee for Aeronautics Report No. 9, 1909, p. 8.

Among the most interesting observations on the relation of wind velocity to altitude are those of Dr. Cesare Fabris * based on some 200 pilot-balloon flights made at nearly equal intervals during the period June 1910 to May 1911 at Vigga di Valle, Italy, the principal ærological station of the Royal Italian Oceanographic Committee. This station is about 25 miles N.W. of Rome and its co-ordinates are as follows: Lat. 42 04′ 41″ N.; long. 12 12′ 43″ E.; altitude 272·4 m. Fig. 1 † gives an indication of the relative velocity at various heights above ground level, i.e. 272 m. Although the curves are for elevations greatly in excess of those of any interest to the designer of radio masts, it is interesting to note that each shows a distinct and regular increase of wind velocity with height, for the range of 272 m to 600 m, i.e. a range of about 1 000 ft.

J. S. Dines also carried out balloon observations at Farnborough in 1912.

### Some Assumptions and Experiments which have been made in the Past.

*Tay Bridge Commission.*—After the disaster to the Tay Bridge, the Commission gave their finding and rules, of which the following are the most important recommendations:—

Wind pressure to be 56 lb. per sq. ft. on girders, trains, etc., on the actual area exposed to wind, plus an allowance of 28, 42, or 56 lb. per sq. ft. according to whether the ratios of the open spaces of the leeward girders to the total area of the outline of the girder are less than ⅔, from ⅔ to ¾, or greater than ¾.

The same Committee also gave it as their opinion that

$$p = \frac{v^2}{100}$$

*The American Society of Civil Engineers*, 1880.—Messrs. Welch, Shaler Smith and Collingwood read a paper and gave the following records of the most violent wind force during tornadoes, etc.:—

Blowing down 3 bridges at 18–27 lb. per sq. ft.
Train derailments at 30·5 lb. per sq. ft.
Destruction of brick houses at 58–84 lb. per sq. ft.
Overturning a barrel of tar at 52 lb. per sq. ft.
Overturning a locomotive at 93 lb. per sq. ft.

They mention the case of a piano being lifted bodily, transported 270 ft. and set down again on its legs without apparent injury.

Ingberg † in 1917, writing of the effects of tornadoes in recent storms, gave the figures, calculated from the damage done, of 27, 31, 37, 29, 45, 39 and 20 lb. per sq. ft. He says: "These pressures (tornadoes) are rarely in excess of 60 lb. per sq. ft., so that structures designed for a load of 30 lb. per sq. ft. with a factor of safety of 2 or more come through intact as to their main structural members."

*Tests made on the Forth Bridge by Sir Benjamin Baker* (1884–1890).‡—In the years mentioned 14 gales were experienced. Records of two were rejected on account of suspected inaccuracy of the instruments. For these tests the following methods of measurement were adopted: A large fixed board or gauge 20 ft. by 15 ft. was erected on top of the old castle on the island of Inch-Garvie, placed so as to be parallel with the bridge, and provided with small disc gauges at its centre and at one of its corners. About 8 ft. from one side of the large gauge was another small, fixed one having an area of about 1·5 sq. ft., and also a second disc of the same size but differing from the others in that it was free to turn. This second disc was kept pointed to the wind by means of a vane. All were read at about 9 a.m. each day for 6 years.

In addition to these tests Sir Benjamin Baker carried out tests with a wind blast on small models of trusses and lattice girders, and satisfied himself that an allowance of 1·8 times the exposed area of the front girders was ample to cover the total wind load on the front and back ironwork.

Four out of the 12 gales were at right angles to the plates used and the following results were obtained:

Small fixed gauge .. 25, 27, 41 and 38 lb. per sq. ft.
Small revolving gauge 30, 25, 35 and 36 ,, ,,
Large fixed gauge .. 17, 19, 27 and 15 ,, ,,

The remaining 8 gales were at about 45° to the gauges, so that the pressure recorded by the instruments was only about 90 per cent of the actual pressure normal to the plate. The actual readings were:—

| Date | Small revolving gauge | Small fixed gauge | Large fixed gauge |
|---|---|---|---|
| | lb./sq. ft. | lb./sq. ft. | lb./sq. ft. |
| 27/10/1884 | 29 | 23 | 18 |
| 28/10/1884 | 26 | 29 | 19 |
| 31/3/1886 | 26 | 31 | 19 |
| 4/2/1887 | 26 | 41 | 15 |
| 5/1/1888 | 27 | 16 | 7 |
| 2/11/1889 | 27 | 34 | 12 |
| 19/1/1890 | 27 | 28 | 16 |
| 25/1/1890 | 27 | 24 | 18 |

As this bridge was designed for 56 lb. per sq. ft. these results show an unnecessarily large factor of safety.

*Bidston Observatory, near Liverpool.*—Pressures were measured simultaneously on a cup anemometer and on a plate 2 ft. square. The instruments used were a Robinson cup anemometer for measuring velocity and an Osler spring-pressure anemometer for recording pressure. The results are given on page 409.

With reference to these figures for Bidston Observatory, it has been pointed out that, as no damage was done, the figures are obviously useless and inaccurate. W. H. Dines in the section on "Anemometers" in the *Encyclopædia Britannica* says that several of these have been erected on the West Coast of England, where in winter fierce gales occur. A pressure of 30 lb. per sq. ft. has never been recorded by them, and pressures exceeding 20 lb. per sq. ft. are extremely rare.

---

* *Reale Comitato Telassographico Italiano*, 1912, Memoria 8, p. 37.

† *Engineering News Record*, 1917, vol. 79, p. 733.

‡ *Engineering*, 1890, vol. 49, p. 219.

That these figures are inaccurate is shown by the tests made on the Forth Bridge, where an average reduction of 40 per cent is necessary on the value of the pressure recorded on the small plate in order to obtain the true value registered on the large plate.

*Eiffel Tower observations* (1889).*—Records were taken at two points simultaneously, viz. at elevations of 69 ft. and 1 064 ft. Of these records, taken on 101 days, the average velocity was 4·9 m.p.h. at the bottom point of observation and 15·7 m.p.h. at the top. The velocity at the top was greater than 17 m.p.h. for 39 per cent of the time and greater than 22 m.p.h. for 21 per cent of the time. The following intensity ratios were found experimentally :—

| Date | Pressure on plate | Velocity |
|---|---|---|
| | lb./sq. in. | m.p.h. |
| 23/1/1884 | 70·2 | 78 |
| 20/5/1887 | 65·2 | 78 |
| 26/1/1888 | 49·2 | 74 |
| 20/11/1888 | 49·0 | 71 |
| 3/5/1888 | 44·4 | 66 |
| 30/3/1886 | 41·9 | 62 |
| 26/10/1884 | 40·6 | 64 |
| 9/12/1886 | 40·4 | 69 |
| 3/2/1887 | 40·1 | 66 |
| 1/11/1887 | 40·0 | 57 |

From this $p = K \times 0{\cdot}0027v^2$, and $K = 3{\cdot}8$ (average) ; or $p = 0{\cdot}01v^2$ (Tay Bridge Commission Report).

$$\frac{V_{\text{top}}}{V_{\text{bot.}}}\begin{cases} = 5 \\ = 4 \\ = 3 \\ = 2 \end{cases} \quad \text{when } V_{\text{bot.}} \begin{cases} = 3 \text{ m.p.h.} \\ = 4 \quad ,, \\ = 5 \quad ,, \\ = 7 \quad ,, \end{cases}$$

*The S.P. Wing experiments at Ballybunion.*†—In 1915, S. P. Wing made a contribution to the knowledge of this important subject, the value of which can best be judged by the remarks of R. Fleming in an article on "Wind Pressures at High Elevations and their Applications to Radio Towers." ‡ The investigation was carried out on 492, 300 and 15 ft. levels, and being on radio masts the results obtained are of considerable practical value. Mr. Wing came to the conclusion, although fully recognizing the incomplete and unsatisfactory nature of the results obtained, that the increase of pressure with elevation follows a law approximating to

$$P = (0{\cdot}00126h + 1{\cdot}16)P_g$$

where $P$ = pressure in lb. per sq. ft. at a height $h$ above ground level ; and
$P_g$ = pressure in lb. per sq. ft. at ground level.

For example, with an assumed pressure, $P_g$, of 27 lb. per sq. ft., corresponding to a wind velocity of 80 m.p.h., the pressure $P$ at an elevation of 820 ft. would be 59 lb. per sq. ft., with a corresponding wind velocity of 118 m.p.h.

### Some Examples of Wind-pressure Assumptions in Connection with Radio Towers and Chimneys.

In 1911, specifications issued by the United States Government for a square tower 200 ft. in height called for a wind pressure of 50 lb. per sq. ft. In a specification issued in 1914 for 300-ft. triangular towers to be erected at Key West, Florida, the specified pressure was 30 lb. per sq. ft. Towers, 600 ft. in height, built at Guam have the wind-pressure assumption of 30 lb. per sq. ft. cast in the nameplates.*

In the case of the tallest self-supporting steel stack in the world, i.e. at the plant of the United Verde Copper Company, of Clarkdale, Arizona, with an elevation of 400 ft. and a diameter of 30 ft., the wind pressure assumed was 25 lb. per sq. ft.†

The brick chimney at Great Falls, Montana, was for a time the highest in the world, being 506 ft. above its foundations with an internal diameter of 50 ft. at the top. The wind-pressure assumption was 33 lb. per sq. ft. of projected area and this factor was determined upon after due consideration of the height, the altitude and the very severe winds prevalent in the locality.‡

A similar chimney made by the same company at Tacoma, Washington, in 1917 is 573 ft. high and 25 ft. in diameter at the top. At Anaconda, Montana, is the highest chimney in the world, with a height of 585 ft. above the foundations and 60 ft. internal diameter at the top. In the design of these two chimneys a wind pressure of 33 lb. per sq. ft. of projected area was assumed.§

In the design of a reinforced concrete chimney 570 ft. high with an internal diameter of 26 ft. 3 in., built at Saganoseki, Japan, in 1916, the wind pressure assumed was 25 lb. per sq. ft. of projected area.||

Marks in his "Mechanical Engineer's Handbook" gives for guyed steel stacks a wind pressure of 25 lb. per sq. ft. of projected area.

The triangular towers at Arlington, Virginia,¶ of which there are two 450 ft. and one 600 ft. in height, were designed for a pressure of 30 lb. per sq. ft., as also were the 600-ft. towers at San Diego, Pearl Harbour and Cavite.

For a standard 820-ft. triangular tower proposed for Fort Monroe, U.S.A., the specification called for 30 lb. per sq. ft. on 1·5 times the area of the front face.**

In connection with these figures R. Fleming says that, according to the U.S. Government formula for towers erected near the coast, the actual wind velocities corresponding to recorded wind velocities of 110 and 100 m.p.h. are 82·9 and 76·1, which (using the formula $p = 0{\cdot}004v^2$) gives 23 lb. per sq. ft. for a recorded velocity of 100 m.p.h., and 27·5 lb. per sq. ft. for a recorded velocity of 110 m.p.h.

---

* *Scientific American Supplement*, 1890, vol. 30, page 12121.
† *Electrician*, 1921, vol. 87, p. 6.
‡ *Engineering News Record*, 1922, vol. 88, p. 438.

* *Engineering News Record*, 1919, vol. 83, p. 662.
† *Ibid.*, p. 500.
‡ *Engineering Record*, 1908, vol. 58, p. 600.
§ *Engineering News Record*, 1919, vol. 83, p. 501.
|| *Ibid.*, p. 501.
¶ *Journal of the American Society of Naval Engineers*, 1913, vol. 25, p. 60 ; *Engineering News Record*, 1919, vol. 83, p. 662.
** *Engineering News Record*, 1919, vol. 83, p. 662.

Mr. Fleming also adds that he believes that with the assumption of 30 lb. per sq. ft. on 1·5 times the exposed area of one face, working stresses of 18 000 lb. per sq. in. in tension and $(18\,000 - 70l/k)$ in compression are permissible for all loadings, where $l$ = length of column in compression, and $k$ = least radius of gyration. His preference is for 30 lb. per sq. ft. on 1·75 times the area of one face, 20 000 lb. per sq. in. for tension and $(20\,000 - 90l/k)$ for compression.

The J. G. White Engineering Corporation built 10 stations in which the 79 masts consisted of a steel tubular pattern built up of half or quarter cylinders, and ranged in height from 300 ft. to 500 ft. In this design a wind pressure of 30 lb. per sq. ft. of projected area was assumed.

R. Weagant in an article on "Design and Construction of Guy-supported Towers" * gave a worked example of a 625-ft. tubular mast. His assumed wind loads were as follows :—

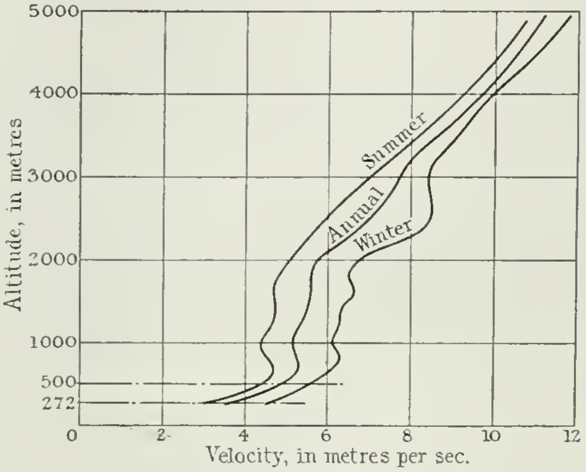


FIG. 1.—Increase of wind velocity with elevation (after Fabris).

Up to 100 ft. elevation, 15 lb. per sq. ft. of projected area.
From 100 to 200 ft. elevation, 16 lb. per sq. ft. of projected area.
From 200 to 300 ft. elevation, 21 lb. per sq. ft. of projected area.
From 300 ft. to top, 25 lb. per sq. ft. of projected area.

*Radio Central Station of the Radio Corporation.*†—In the recently constructed station at Port Jefferson, Long Island, U.S.A., the towers, of which there will ultimately be 72, are 400 ft. in height. The wind load assumed in the design was 30 lb. per sq. ft. on twice the projected area of one face for the top 300 ft., and a similar figure on 1·5 times the face for the lower 100 ft.

*Radio Station at Croix D'Hins, Bordeaux, France.*—The eight towers, each 820 ft. in height, were designed by the Bureau of Yards and Docks, U.S. Navy, and constructed by the Pittsburgh Des Moines Steel Co. The wind pressure assumed was 30 lb. per sq. ft. on 1·5 times the area of one face.

*Marconi Company 820-ft. tower specification.*—In a specification issued in 1919 by the Marconi Company for 820-ft. steel towers, the wind pressure specified was 30 lb. per sq. ft. on the whole of one face in the direction of the wind, and a similar pressure on the back.

*Imperial Wireless Commission specification.*—In a specification recently issued by the General Post Office, covering 820-ft. masts for the Imperial wireless chain, a wind pressure of 60 lb. per sq. ft. over the entire height of the mast is specified on 1·6 times the front-face area for triangular masts, and 1·8 times the front-face area for square-section masts.

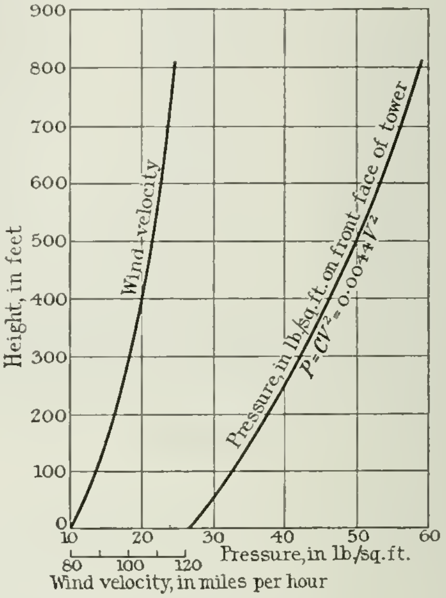


Fig. 2.—Increase of velocity and pressure with elevation (after Wing).

*Head frames.*—M. S. Ketchum in his "Structural Engineer's Handbook" specifies for wind loads on head frames a pressure of 50 lb. per sq. ft. acting on the projection of the members of the head frame. R. Fleming says: "The load of 50 lb. seems excessive even for head frames in locations subject to high winds."

## CONCLUSION.

Many more examples of the variety of specifications employed in the past for the pressures due to wind could be quoted, but sufficient have been given to prove considerable difference of opinion. By tabulating the data and reducing to a common form of expression, e.g. the total pressure on the structure in lb. per sq. ft. of the front face, the divergence of opinion can readily be seen to be from 15 to 112 lb. per sq. ft.

In building design, the assumption that the wind pressure at the top is the same as at ground level may not be productive of any harmful results. In radio mast and tower design the load due to the wind is, however, the chief load. Masts when unloaded are held vertical and designed to lie in a straight line, or as an arc of a circle when fully loaded. A wrongful assumption as to wind-pressure distribution from the top of the structure to the bottom can readily upset the designer's calculations as to the position which the mast will take up in a gale.

---

* *Proceedings of the Institute of Radio Engineers*, 1915, vol. 3, p. 135.

† *Engineering News Record*, 1922, vol. 88, p. 438.

In order to appreciate the economic waste which is present in employing 60 lb. per sq. ft., for example, over the entire height of an 820-ft. mast, as opposed to a graded wind pressure of from 27 to 59 lb. per sq. ft. as shown on Fig. 2, the comparative quantities of structural steel, stay wire and concrete have been calculated. If, as is very possible, the assumption of 27 to 59 lb. per sq. ft. should be excessive and one-half of these values be sufficient, then the further possible percentage saving is also shown.

| | 60 lb. | 27–59 lb. | 13·5–29·5 lb. |
|---|---|---|---|
| Structural steel .. .. | 128 | 100 | 75 |
| Stay wire .. .. | 140 | 100 | 50 |
| Concrete .. .. .. | 155 | 100 | 50 |

We have no definite knowledge as to how wind pressures, especially high wind pressures, vary with elevation, but it seems clear that they are not the same at the ground as at, say, an elevation of 1 000 ft., and the evidence points to the top pressure being more than double the pressure at the ground, so that it is not a negligible factor. The designer then seems to be more nearly approximating to actual condition if he adopts such a curve as Fig. 2 than if he assumes the same pressure both at the top and at the bottom of the structure. In our own design work we use this curve for lack of knowledge of one which more nearly approximates to actual conditions. Perhaps the discussion on this paper will bring forth hitherto unpublished data taken at radio stations or elsewhere, which will cause us to modify our views.

If it prove that no more data exist on this important subject than have been brought out in this paper, it seems to indicate that we should attempt to gain this knowledge without delay. With the large number of high radio masts and towers which have been built in recent years, there are many opportunities for fixing recording anemometers or pressure indicators at ground level, at the top and in as many intermediate positions as funds will permit. If this paper should serve to inspire any of the owners of high radio masts or towers to equip them with the necessary recording instruments with a view to filling a void in our knowledge, it will not have been in vain. The Imperial Wireless Commission, the Radio Research Board, the National Physical Laboratory and the British Meteorological Office acting in collaboration with the owners of high masts could soon produce a much more accurate solution of this important problem. If the Wireless Section of this Institution would take an active interest in the solution of this problem, more satisfactory data would soon become available.

In conclusion, one cannot do better than quote the *Encyclopædia Britannica* in connection with power-transmission towers, to the effect that "the actual possibility of wind pressure is very generally overestimated and has resulted in much needlessly costly construction."

## APPENDIX.

*Summary of some Wind-pressure Assumptions.*

| | Wind pressure | Value of $K$ | Pressure on front face | Remarks |
|---|---|---|---|---|
| | lb./sq. ft. | | lb./sq. ft. | |
| Tay Bridge girders .. .. .. .. | 56 | + 28 | 84 | Open spaces $< \frac{2}{3}$ total outline |
| Tay Bridge girders .. .. .. .. | 56 | + 42 | 98 | Open spaces $\frac{2}{3}$ to $\frac{3}{4}$ total outline |
| Tay Bridge girders .. .. .. .. | 56 | + 56 | 112 | Open spaces $> \frac{3}{4}$ total outline |
| Forth Bridge design .. .. .. .. | 56 | 1·8 | 101 | Sir B. Baker considers excessive |
| U.S. Government .. .. .. .. | 50 | 1 | 50 | 200 ft. square tower, 1911 |
| U.S. Government .. .. .. .. | 30 | 1 | 30 | 300 ft. triangular towers, Key West |
| U.S. Government .. .. .. .. | 30 | 1 | 30 | 600 triangular towers, Guam |
| United Verde Copper Co. .. .. .. | 25 | 1 | 25 | 400 ft. steel stack ; 30 ft. top |
| Great Falls, Montana .. .. .. .. | 33 | 1 | 33 | 506 ft. steel stack ; 50 ft. top |
| Tacoma, Washington .. .. .. .. | 33 | 1 | 33 | 573 ft. steel stack ; 25 ft. top |
| Anaconda, Montana .. .. .. .. | 33 | 1 | 33 | 585 ft. steel stack ; 60 ft. top |
| Saganoseki, Japan .. .. .. .. | 25 | 1 | 25 | 570 ft. concrete tower |
| Marks's " Handbook " .. .. .. .. | 25 | 1 | 25 | Recommended for guyed steel stacks |
| Arlington .. .. .. .. .. .. | 30 | 1 | 30 | 450 ft. and 600 ft. towers |
| San Diego.. .. .. .. .. .. | 30 | 1 | 30 | 600 ft. towers |

[*Continued on page* 412.

APPENDIX—*continued.*

*Summary of some Wind-pressure Assumptions.*

| | Wind pressure | Value of $K$ | Pressure on front face | Remarks |
|---|---|---|---|---|
| | lb./sq. ft. | | lb./sq. ft. | |
| Pearl Harbour | 30 | 1 | 30 | 600 ft. towers |
| Cavite Harbour | 30 | 1 | 30 | 600 ft. towers |
| Fort Monroe | 30 | 1·5 | 45 | 820 ft. tower |
| R. Fleming | 30 | 1·5 | 45 | General recommendation |
| J. G. White & Co. | 30 | 1 | 30 | 79 tubular masts |
| R. Weagant | 15 | 1 | 15 | Round masts, up to 100 ft. |
| R. Weagant | 25 | 1 | 25 | Round masts, over 300 ft. |
| Port Jefferson | 30 | 1·5 | 45 | 400 ft. towers, up to 100 ft. |
| Port Jefferson | 30 | 2 | 60 | 400 ft. towers, over 300 ft. |
| Bordeaux | 30 | 1·5 | 45 | 820 ft. towers |
| Marconi Co. | 30 | 2 | 60 | 820 ft. specification |
| Imperial Wireless Commission | 60 | 1·6 | 96 | 820 ft. mast |
| Head frames | 50 | 1 | 50 | Fleming regards as excessive |

## DISCUSSION BEFORE THE WIRELESS SECTION, 10 JANUARY, 1923.

**Dr. W. H. Eccles:** The information collected in the paper is, of course, largely meteorological, but it is also interesting to constructional engineers because it gives definite data and facts about existing structures of great altitude. The author emphasizes two main issues. The first is that the grading of the wind pressure with height ought to be adopted in designing masts and towers for wireless purposes, and the second is that many of these high structures are unnecessarily costly because windage and safety factors of too large value have been assumed by cautious designers. With regard to the first point, the grading of wind pressure, the author discusses the subject from the point of view of measurements in the open air under fairly ordinary conditions. It is well known that in all ordinary air movements the velocity at ground level is much smaller than that at a height of 1 500 ft., where the velocity attains a value approximating to the theoretical value computed from the isobars on the synoptic charts. This distribution of velocity seems to hold good also in heavy winds and even in gales; but it is not for those conditions, which we may call peace conditions, that the designer of a mast has to work. No mast reasonably strong has fallen down under ordinary air movements. One has to design for a time of crisis when the motion of the air is so turbulent that probably all the data and theory which we have had put before us break down. For example, if two extreme cases of air movements, such as those in England and those in Hong-Kong, be considered, it will be found that there are at least two different types of atmospheric crisis. The type we have in England usually appears as a "line squall." These are not very frequent—possibly they come about once in 10 years on the average—but it is for such conditions that the designer of masts has to prepare. He dismisses all considerations that are based on the measurement of air velocities during the preceding 10 years of peace; he has to think of the 30 seconds of crisis. During a line squall the motions of the air are quite different from those in normal conditions. In these islands the line squall is produced by a cold wind usually coming from the west or the north-west almost broadside on to a mass of warm air which would otherwise be moving from the south. Because the velocity above is greater than the velocity below, the upper layers of the cold air push ahead of the lower layers and the border between the warm and cold air leans forward, as it were, as the motion takes place, and consequently large masses of cold air fall through the warmer air from a height of about 2 000 ft. The warm air underneath the crest of this wave of cold air breaks like a big bubble through it, and the consequence is a horizontal rolling progress of the front of the cold current of air. That rolling motion seems to have its centre at a height of about 1 000 to 1 500 ft., and it is therefore quite possible to experience for an instant a velocity near the ground greater than 60 m.p.h. and a velocity of, say, only 40 m.p.h. at 1 000 ft. up. On account of this rolling motion we may have for a few seconds a complete reversal of the conditions of which the author has told us. That, however, is not the worst of the matter from the point of view of the design of high towers, because when the warm air suddenly rises in the atmosphere the water vapour in it condenses and huge volumes of rain and hail are formed, which, descending through this cold wind below, gather a horizontal component of velocity as they fall. When the momentum of the rain, hail or snow is added to that of the wind, much higher pressures than those mentioned in the paper are obtained. What we really want, it seems to me, are the statistics of the total pressures on structures during the times of crises. The statistics taken during the preceding 10 years of peace are not of any direct value. They are of indirect value in the sense that every scrap of knowledge which we obtain enables us to make better calculations next time, or shows us how from that knowledge we can compute what happens in the turbulent condition of the atmosphere that I have tried to describe. The other extreme case I referred to, the typhoon, consists of a rotation of the air around a vertical instead of a horizontal axis. At a place like Hong Kong it seems to be expected that certain tracts of country are sure to get a typhoon every few years, and if the buildings are light enough they get removed at fairly regular periods. There are exceptions, of course, which stand for 50 or 100 years, but the insurance companies would not base their premiums on such cases. The other thing I should like to mention—and I think the author has not referred to it—is that we really must take account of the dynamics of the matter in the design of these structures. A big mast in a turbulent atmosphere rocks first one way and then the other, and the motion may be as much as 10 ft. at the top of an 800-ft. mast. This motion must tend to take place, as in the case of every fairly rigid body, about a dynamic centre fairly near the centre of gravity. The problem becomes different according to whether the mast is fixed into a massive block or has a pivoted foot. I do not know that one type is more dangerous than the other in practice, but we have less experience with the one with the swivel base. The dynamics of both prove to be very difficult, chiefly on account of the effects of the guys. If it be assumed that the mast tends to rock about the centre of gravity, it will be found that very big thrusts are imposed sideways on the base. To prepare for this the design should be such that the centre of gravity of the mast will be fairly low, lower in the case of a pivoted mast than with one footed in concrete. When all these factors are taken into account, one feels it is best to use a rather large windage value and so keep the centre of gravity low. And there are other reasons for this. The author quotes from the *Encyclopædia Britannica* that many structures are needlessly costly, but whether that is so depends upon the circumstances. If by making a structure safe 20 per cent is added to the weight, seeing that labour is such a large factor of the cost of a mast, it may be that 10 per cent is added to the cost. This 10 per cent, if it enables the mast to survive three squalls instead of falling down at the first, will be a wise insurance. For it is necessary to consider how much business would be lost while erecting a new mast after one had fallen, and also, in the case of strategic stations, whether great dangers might arise if masts were blown down. I therefore do not agree with the writer of the article in the *Encyclopædia Britannica*, but am in favour of a very good margin of insurance when not only possible commercial losses but also strategic aspects have to be considered.

**Major A. S. Angwin**: There is no doubt that the paper is very valuable as indicating the great discrepancy between the experimental data of wind pressures at high elevations and the assumptions made in the design of towers. I think the conclusion can be drawn that the data in the paper from different sources indicate so many discrepancies that it is very difficult indeed to form any law which would safely meet the case of the variation of pressure or velocities throughout a structure such as an 800-ft. or 1 000-ft. mast. There are some other data not quoted in the paper which rather bear on that assumption. Reference is made to the classical experiments on the Forth Bridge by Sir Benjamin Baker, but during a period of five years, 1901 to 1906, covering a much longer time, further records were made on the Forth Bridge during gales, and over that period, at a height of 378 ft. above sea level, pressures as high as 65 lb. per sq. ft. were recorded. If a figure of that order were applied to the formula suggested by the author, it would result in very much higher pressures than the assumptions which are made; they work out at something like 85 lb. per sq. ft. at the top of an 800-ft. mast, down to 40 lb. per sq. ft. at the bottom of the mast. The figure of 85 lb. is an incredibly high value and indicates that it is not safe to assume a formula of that nature. Further data published by the Meteorological Office in 1918 give values of wind velocities and also gust velocities at varying heights up to about 100 m. The analysis of the form of the curve of those results appears to indicate that at steady wind velocities there is a very marked increase of velocity with height up to about 100 ft. At greater heights the slope of the curve decreases very much. Neither of those results appears to agree at all closely with the suggested linear law attributed to Wing. From the evidence available I think that the conclusion to be drawn is that whilst for steady winds of moderate strength an assumption of the nature suggested may be made, such an assumption does not appear to be applicable for gales or for gusts. In connection with the design of structures, the designer is concerned with the concentrated gusts. In the recorded figures for the Eiffel Tower on page 409 it will be noticed that the ground velocities are very small, i.e. from 3 to 7 m.p.h. At 3 m.p.h. with a velocity ratio of 5 the wind at the top of the mast will be 15 m.p.h., whereas at 7 m.p.h. the velocity ratio is only 2 and the actual velocity of the wind at the top of the tower will be 14 m.p.h., i.e. less than at the lower figure of 3 m.p.h. at the bottom. It would seem to be a more reasonable assumption, if it is conclusive that the pressure is not constant throughout the whole of the length of the mast, to assume a steady load corresponding to a pressure of about 30 lb. per sq. ft. for the whole of the structure, and superimpose thereon a live load of the order of 20 to 30 lb. per sq. ft., which might be applied in lengths not exceeding 100 ft. That would appear to correspond more closely to the conditions which might occur during a violent storm. The question of the allowances to be made for wind pressure on the back of the mast is briefly referred to in the paper. There must now be a great deal of data available from experimental determinations. The only possible way to find the exact value of $K$ is by experimental determination in wind tests, and, as suggested by the author, any data of that nature would be of very great help in treating the question of the design of masts.

**Mr. Oluf Trost**: The shape of the curve shown in Fig. 2 is largely dependent on local conditions and it may for the same mast vary for different directions of the wind. More recent Eiffel Tower observations give a different curve altogether. On the other hand, a wind velocity of 100 m.p.h. or more has not yet been recorded since the tower was built, 33 years ago, which perhaps accounts for the fact that masts in France are made lighter than one would care to make them in other parts of the world. I do not agree with the figures which the author puts forward to show what economy could be obtained in material with a reduction in wind pressure. In mast construction there are so many factors to take into account that the economic waste in assuming a fairly high wind pressure is not so very large. In a well-designed construction consideration has to be given to minimum sizes of material, upkeep, erection and many other things. I quite agree that it would be of great importance to obtain as many statistics as possible from all parts of the world, especially as to the probability and regularity of "super-wind" velocities occurring in different places. It would also be of great interest to learn whether there is any relation between the average wind load and the maximum wind load, including the frequency with which the latter occurs. It might be possible to find some relation between these factors so that it would be more easy to know with some certainty the maximum loads to which a mast will be exposed, when built in a certain place. Finally, I should like to point out that the figures mentioned as being the wind pressures specified by the Marconi Company are now out of date and that the designs are based upon wind pressures of from 30 to 50 lb. per sq. ft. of surface exposed to the wind, the figure varying with the height of the masts.

**Mr. Andrew Gray:** I agree with the author that, in general, wind pressure is more than amply provided for in present practice by reason of the ample factors of safety. The problem is, however, complicated by the presence of wind eddies. In some cases these eddies add to the loads by producing oscillations, while in other cases they may reduce the load; for example, a long span of wire may be locally heavily loaded but as a whole partly supported by the eddies. I remember in particular the effects of the hurricane on the island of St. Vincent, West Indies, in September 1898. Almost every house was unroofed, including the library—a good stone building in Kingston—although the walls remained standing, and the branches of the trees were torn off the trunks, but few of the trees were blown down. In the case of an avenue of palm trees leading to Government House the heads of the palms were torn off but the palm trunks, some 30 or 40 ft. in height, remained standing. There was not the slightest doubt in my mind that in this case the major damage was done by the eddies. In the case of another hurricane, that in Fiji in 1912, it was reported to me at the time that the roof of the wireless station engine-house was torn off, but the mast—a 150-ft. sectional steel stayed mast with a wooden top—remained standing, again indicating the presence of eddies. The effect of these eddies is to produce great pressure at particular instants over small areas, but the maximum pressures do not occur simultaneously over the whole of a large area or an extended structure such as a mast or aerial. On the other hand, these eddies where they do occur act to a considerable extent like a blow and have to be considered in that way, and one has to be satisfied that in any mast or tower design a suddenly applied local blow will not cause stresses in excess of those allowed by the dead-load calculation and factor of safety.

**Professor C. L. Fortescue:** The load carried by a mast arises from the wind pressure on both the mast and the aerial. If the proportion of the load due to the latter is large it follows that the wind pressure at the top of the mast is the most important factor. Perhaps the author will say in his reply what relative values he has actually found for these two contributions to the total load. If a large factor of safety is allowed for the load arising from the aerial it may explain how it is that satisfactory service has been given by those masts in which low wind pressures have been assumed.

**Professor G. W. O. Howe:** This is a very highly specialized subject, appealing only to a small number of wireless engineers. When reading the paper I had some doubt as to what was intended when it is stated that the specification called for certain wind pressures—whether the masts were supposed to stand satisfactorily at those specified wind pressures with a reasonable factor of safety, or whether they are the limiting wind pressures at which the tower is supposed to collapse. I am surprised that so little is said in the paper as to the factor of safety to be allowed in the various cases, as it seems to me to be useless to specify any definite wind assumption without at the same time specifying the factor of safety to be allowed; I should like some further information on this point. The author mentions the Bidston experiments and states on page 409: "That these figures are inaccurate is shown by the tests made on the Forth Bridge, where an average reduction of 40 per cent is necessary on the value of the pressure recorded on the small plate in order to obtain the true value registered on the large plate." I do not know why one is justified in assuming that the large plate should give the true value. Two plates were put up and it is assumed that because they differ the large plate gives the true value. I do not know whether there is any proof that a still larger plate would not have given an entirely different value.

**Mr. A. C. Brown:** Has any account been taken of the effect of snow on the wires? I know of cases where the temperature at the commencement has been rather high, with wet snow. Afterwards, when the temperature fell and the snow was frozen, the wires became of very large diameter. I think that that point has to be considered, as it is quite possible that the final diameter of the aerials when covered with ice will be 4 or 5 inches.

**Mr. S. P. Wing** (*communicated*): The paper brings under discussion a subject the importance of which I think is not ordinarily realized by electrical engineers. An electrical engineer is ordinarily responsible for the complete installation of large wireless installations. He gives great care to the most efficient type of electrical equipment to be used and works carefully to gain an extra efficiency of perhaps 10 per cent in his electrical apparatus. Yet when it comes to the question of the aerial structure he is often content to specify in a general way the wind and antenna loads and leave the mechanical design of the masts and antenna to the civil engineer, without realizing that these two items largely control the cost of this portion of a wireless station. Since the aerial structure with the antenna represent from 40 to 60 per cent of the cost of a complete station, it is seen that unnecessarily severe loadings in this regard may easily run away with the 10 per cent saving he has effected by efficient electrical design. For example, the electrical engineer may have used a large amount of wire in his antenna (thus causing heavy mechanical antenna loads) to gain an extra 5 per cent antenna efficiency, when a greater saving could perhaps be made by tightening the antenna and thus gaining effective height. Alternatively, a smaller antenna load could be used and a higher mast built. The author gives comparative figures showing the average charge of certain large items which make up the cost of a wireless mast under three conditions of wind loading. Approximately these represent two-thirds of the entire cost, the other items not varying with the wind loading. On this basis the percentage cost of a mast under the three conditions which he has shown is 127, 100 and 72. Wireless masts have been built under the first two of these classes of loading. Assuming 8 masts 800 ft. high, this might represent an expenditure of £125 000, 27 per cent of which is £34 000. With such sums in question and with larger stations yearly being erected it would seem that the author's plea for more data on wind loading is well justified and that interested parties could well afford to spend the few hundred pounds necessary to obtain these data. I believe that the confusion existing in regard to wind specifications, examples of which are so numerous in the paper, is due to the fact that the wind loads are those assumed by structural engineers, these loads in ordinary design being of little economic importance. Equally in wireless masts of small heights such loading is of small matter. Yearly, however, the height of masts has increased and with this the importance of the wind loading, until now it is the major load. No bridge designer would think of basing his design on a haphazard covering load, and equally in the future no electrical engineer should specify the wind loading for a wireless mast without the most careful consideration, for otherwise the civil engineer is bound in the most vital factor affecting the economics of his design. I realize the necessity for a mast in which there can be no question of failure, but if larger factors of safety are required than those used in ordinary building practice such factors should be obtained by increasing the safety factor rather than by specifying an unnecessarily large wind load. Take, for example, a uniform specification of a loading of 60 lb. per sq. ft. We have no knowledge of such a wind loading occurring near the ground (say under 100 ft. elevation). We surmise that such a load may occur at 800 ft., though such velocities as this loading implies have seldom, if ever, been measured. Obviously, if we wish to ensure the safety of our structure, it is wiser not to assume a uniform heavy wind load causing smaller factors of safety at the top of mast than at the bottom, but to use a graded load as the author suggests or (perhaps better) adopt the suggestion of Major Angwin and superimpose a graded live load on a probable wind load. To adopt such a specification intelligently, however, we must have the further data for which the author appeals. Throughout the paper he lays emphasis on wind-pressure assumptions. This is natural, as he is quoting from past experience and records. I believe that such past procedure is wrong and that it is something which wireless engineers can correct. The majority of wind records are based on velocities which are measured direct. Where pressure is measured this is of little use to the wireless engineer. Such a statement would have been difficult of explanation a few years ago, but with the advent of the aeroplane it is increasingly realized that for every different surface the factor $K$ (in the common formula for changing velocity to pressure, i.e. $P = KV^2$) varies. For this reason the pressure as measured by a Pitot tube bears little relation to the pressure on, say, a long angle. From this it follows that in comparing two mast designs of different type but to a common specification of, say, 30 lb. on $1\frac{1}{2}$ times the front-face area, no true decision can be made as to their relative strength for, depending upon the type of mast and size of members, the factor $K$ varies. Under a given wind velocity the effective loads on the mast, as computed by the specification with a constant factor $K$, may not represent the true state of affairs. The only satisfactory method is for the specification to be in terms of velocity and then for designers to have small-scale models of the proposed structure tested in wind tunnels to determine the coefficient $K$. This can be done at small expense, and an accurate knowledge of the loads which given wind velocities will impose can thus be obtained. I have tried to show above how one of the uncertainties of wind loading can be eliminated. If the paper and the discussion induce the authorities to make the experiments which the author suggests, I believe that electrical engineers will be in a position to issue wireless mast specifications which will ensure that the aerial system is designed as efficiently as the electrical apparatus.

**Mr. C. F. Elwell** (*in reply*): Dr. Eccles gives a very interesting explanation of meteorological conditions in England, and also in Hong-Kong, and points out the necessity for designs to meet the two different conditions of wind loading. But from my experience with high masts in heavy winds I cannot agree that the motion may be as much as 10 ft. at the top of an 800-ft. mast. In the design of an 800-ft. mast I use a deflection of 1 per cent at the top; this represents an assumed maximum movement of 8 ft., and correspondingly smaller movements at each of the lower stay points. Now, due to gusts and eddies the tower does oscillate, not, however from 8 ft. on one side of the vertical to 8 ft. on the other side, but, for example, 1 ft. back and forth from the line of the position which it has taken up due to the steady wind pressure, or a total movement of only 2 ft. The average velocity, and with it the pressure which holds the mast away from the vertical, tends to increase and decrease rather slowly due to the effect of gusts, perhaps varying not over 10 per cent from the mean value. The inertia of the mast and its stays has also to be considered, in view of the fact that the gusts are of relatively short duration. That the thrusts on the pivoted bases may be very big is also doubtful. Pivoted masts up to 850 ft. have been constructed. The figure for the horizontal component acting at the bottom is only a few per cent of the total vertical load, and this horizontal thrust is actually taken up by the horizontal force due to friction from the large vertical loads. It is usual, however, to provide horizontal stops as an additional precaution.

Major Angwin adds some interesting data to those which I have tabulated. I have not been able to find the data to which he refers and I should be pleased to know where they are to be found. Much of the pressure data published previous to 1910 is faulty, due to the inaccuracy of the formulæ changing measured velocities into the desired factor pressures. It is possible that the pressure of 65 lb. mentioned is due to this, and is not a corrected figure corresponding to the modern formula. It must be remembered that, from the point of observation, the Forth Bridge is 378 ft. above ground or sea level. I know of practically no records in England of wind pressures as high as 30 lb. close to the ground, and only three or four of 30 lb. at 200 ft. elevation (Pendennis Castle). Major Angwin's suggestion of a steady loading of 30 lb. with a superimposed live load of the order of 20–30 lb. per sq. ft. in lengths not exceeding 100 ft. can be plotted in the form of a curve, if applied to a mast of, say, 800 ft. in height. This curve would have a form somewhat similar to that proposed. But due to the rarity of 30-lb. winds at ground level it would seem to be unnecessary to add any live load here. In effect the curve of Fig. 2 can be considered as adding 15 lb. at 400 ft., and 30 lb. at 800 ft. elevation to a ground pressure of about 30 lb. If more data could be recorded and the shape of the curve of increase of wind pressure with the height more accurately obtained, I think that engineering economics would be better served than by the many and varying guesses of the past. One thing to be said in favour of Mr. Wing's curve is that it is the only attempt of which I know to measure actually the velocities at heights low enough to interest radio engineers, and it is fairly well substantiated by the measurements of Dr. Fabris. Of course the topography of the neighbourhood has some bearing on the increase of pressure with height, especially from ground level to 100 ft. The question of allowances to be made for wind pressure on the back of the mast was only briefly referred to in the paper, as it is proposed to make a further communication on this subject at a later date.

Mr. Trost points out that consideration has to be given to minimum sizes of material, etc., and this is well recognized, otherwise the figure for 13·5/29·5 lb. wind assumption would have been 50 for steel, instead of 75. The figures given are round figures, but were obtained by working out a complete design which had already been made for a 27/59 lb. wind. However, if any one of the three assumptions be adopted, different section lengths, etc., would be employed in order to obtain the maximum economy. With a 60-lb. wind, for example, assumed on the bottom section of a mast, the sections would be made shorter than with a 30-lb. wind, because of the large increase in stresses due to beam action. It is a recognized fact that the fewer the stays employed the heavier the steel in the mast. A 9-stay design with a 60-lb. wind all over becomes as heavy as a 5-stay design with the 27/59 lb. assumption.

Mr. Andrew Gray gives interesting particulars concerning hurricane figures. I am sceptical, however, as to the effect of eddies being like a blow, or, if so, it is my belief that they are counteracted by the inertia of the mast and its stays.

In reply to Professor Fortescue, the higher the mast the less important becomes the load due to the wind on the aerial. In a given design for a very heavy aerial, the load per column at the bottom of the mast was 6 per cent for the aerial and 94 per cent for the wind load and dead weight of the mast.

The question of factors of safety, mentioned by Professor Howe, was not brought into the paper as the engineer entrusted with the design would use the factors of safety usually employed for the class of material in question. Structural steel is usually worked on the basis of $18\,000 - 70\ l/k$, where $l$ = length of unsupported section, and $k$ = least radius of gyration of the member. This represents roughly a factor of safety of 2. For the stays, factors of safety of from 3 to 4 are generally specified. The plates employed in the Forth Bridge experiments were intended to have a fixed relation to the sizes of girders used on the bridge. The most accurate method of obtaining the effect of the small and large areas in a structure under the action of wind pressure is to construct a model and test it in a wind tunnel.

Mr. Brown points out the possibility of wires becoming very large due to deposits of ice. This is a problem which has to be faced on the east coast of the United States, where in some stations electrical methods are employed for melting the ice. From a structural point of view there is not much danger in omitting the area offered by these large diameters, because it has been amply borne out in practice that high winds and coated wires do not occur simultaneously. The increasing wind pressure tends to break off the ice, and so diminishes the danger.

Mr. Wing refers to the economics of the subject, and the question is summed up in the possibility that the expenditure of a few hundred pounds might save many thousands of pounds in future expenditure. Present wireless plans call for some 50 masts of the order of 820 ft. in height, and these may be erected in the next three years. They represent an investment of a considerable sum of money and warrant the expenditure of a substantial sum in experiments on wind pressure, wind resistances, stay wire with minimum stretch, etc.

# THE MAINTENANCE OF VOLTAGE ON A D.C. DISTRIBUTION SYSTEM BY MEANS OF A FULLY AUTOMATIC SUBSTATION.

By P. J. Robinson, Associate Member.

(*Paper first received* 29*th November, and in final form* 19*th December*, 1922; *read before* The Institution 1*st February, before the* North Midland Centre 6*th February, before the* North-Eastern Centre 12*th February, before the* Mersey and North Wales (Liverpool) Centre 19*th February, before the* North-Western Centre 20*th February, before the* South Midland Centre 21*st February, and before the* Scottish Centre 13*th March*, 1923.)

### Summary.

The paper describes the considered methods of meeting a particular case of voltage-drop in a large direct-current lighting network and for bringing into use the maximum amount of its copper with a minimum of cost.

A fully automatic station was chosen in this instance for the reasons stated, and the author in discussing the subject has not attempted to review the relative merits of different types of automatic stations, but rather the method of dealing with a particular problem, and with this end in view has described the station which has come under his immediate control.

So far as the author is aware, the plant described is that of the first fully automatic station in this country, for any purpose, and of the first fully automatic station in existence operating a three-wire system.

---

The gradual growth and expansion of our cities owing to increased industrial activities and better transport facilities have brought large areas that were thinly populated suburbs into close touch with the city, and caused them to be more densely populated. This has meant that the original electric supply systems laid down, in some cases many years ago, have gradually extended until such time as the length of feeders has become troublesome owing to the voltage-drop.

In the event of the system being originally an alternating-current system and remaining so, this has been overcome by installing transformers at suitable points in the system to maintain the pressure. Where, however, the system was originally a direct-current one, the engineer was faced with a much more difficult problem, more particularly in the residential areas, as d.c. plant had to be installed, which meant buildings to house it and staff to operate it. The latter item is particularly expensive, as the stations are worked on a more or less low load factor; also the staff salaries and operating costs do not increase in direct proportion to the capacity of the station. This fact has led to larger and fewer substations at long distances apart.

The more extensive use of domestic apparatus has had the effect of raising the average load taken by consumers from ½ kW to 1 kW for lighting, up to 5 or 6 kW on the average when domestic apparatus such as radiators, cookers, vacuum cleaners, irons, etc., has been installed. This has necessitated more feeding points along the system to make full use of the copper laid down. Assuming copper at 1 000 amperes per square inch, in some cases only 30 per cent is available owing to the voltage-drop due to the length of feeders, which voltage-drop is, after all, the limiting factor in fixing the value of the distribution system.

This problem of maintaining a more constant voltage over the whole network, and at the same time keeping down operating costs and capital costs, has been exercising the minds of many electric supply engineers in this country, and Liverpool is in much the same position as other authorities. Recognizing that the matter had to be dealt with, and appreciating the alternatives, i.e. to lay new feeders, or to change over sections of the distribution to a.c. supply, building up either a new distribution system or using old d.c. mains for a.c. supply (the latter being almost prohibitive, due to the cost of changing consumers' apparatus, motors, battery-charging sets, and many other pieces of apparatus not fitted with universal motors), it was finally decided to try to deal with the matter by installing fully automatically operated stations at different points of the system, thereby reducing operating costs to a minimum, and at the same time enabling the existing mains to be utilized to the best advantage.

Fully automatic control and remote automatic control of converter plant have been in use in America for lighting and traction purposes and also in Switzerland for traction purposes, for some time past.

Remote control has also been in use in this country on several systems with more or less success, but British engineers appear to have fought shy of fully automatic control, and it has been left to Liverpool to lead the way in this direction. The Electric Supply Department decided that all conditions existing in Liverpool could be met by this control and that, apart from periodical inspection of plant, operating labour could be eliminated.

Acting on this decision a general scheme was evolved for the control of a three-wire system with the conditions that would have to be met in Liverpool, also covering various points on which we must insist. Having chosen a site adjacent to Walton Town Hall, midway between two of our existing manually operated substations, namely, Cobbs Quarry and Rice Lane, we submitted the scheme to various manufacturers of automatic gear. The scheme and conditions were as follows:—

(1) The station to have a capacity of 500 kW, with room for extension.

(2) The station should cut in after the pressure on the low-tension feeder bars had fallen and remained low for a predetermined time. (This time-lag was to avoid the station cutting-in with temporary falls in voltage.)

(3) The station should cut out after the current on the busbars had fallen and remained low at some fixed figure for a predetermined time; the latter was to avoid the station cutting-out

with temporary falls in load. This was also to enable the existing manually-operated stations to pick up the load when the conditions were such that the voltage could be maintained at normal.

(4) The station to operate plant running across a three-wire system, 230 volts between each outer and the neutral, and to maintain a balance in pressure.

(5) The station should operate in parallel with other stations, and other plant in the same station at a later date.

(6) If the load demanded due to existing manually operated stations shutting down was greater than its capacity it should not cut in, and, if already running, the output should be limited to the capacity of the plant.

(7) In the event of a fault on either the negative or positive side of the system, the automatic switch controlling that particular circuit should operate to cut it out, without interference with any other circuit.

(8) In the event of a short-circuit on the outers of a feeder that feeder should be cut out without interference with any other circuit or the running of the plant generally.

(9) The middle wire of the system being earthed through a limiting resistance at the manually operated stations, it was decided to deal with an earth fault from those stations.

The above conditions having been agreed upon, arrangements were made for dealing with them satisfactorily, and also to meet any difficulties due to faults on the plant itself or any connections therewith. It was then decided to proceed with a station equipped as follows:—

(1) One tap-started 500-kW rotary converter (with brush-lifting gear) coupled through its transformer to the 6 000-volt, three-phase, 50-period supply on the one side, and on the other to a three-wire system with 460 volts across the outers and 230 volts to the middle wire, the latter being connected to a tapping on one leg of the transformer supplying the rotary converter.

(2*a*) One high-tension cubicle of moulded stone equipped with an electrically operated oil switch with alternating-current closing coil; this switch to control the rotary converter.

(2*b*) Two liquid fuses to control the operating transformer (15 kVA) which supplies the operating coils on most of the relays and must therefore be permanently connected to the line.

(2*c*) One three-phase potential transformer for various instruments.

(2*d*) Necessary isolating switches.

(3) Low-tension d.c. panel for rotary converter, equipped with knife switches and electrically operated contactors in the main circuit, with ammeters on each pole, a voltmeter, and field regulator.

(4) Low-tension feeder panels for control of four three-wire feeders, equipped with electrically operated contactors in the main circuit and knife switches in the operating circuit to control the main contactors in the event of a feeder requiring to be "laid off."

(5) Other panels to have mounted thereon numerous relays, devices and contactors, the description of which will be found in Appendix A, and the operation of which will now be described.

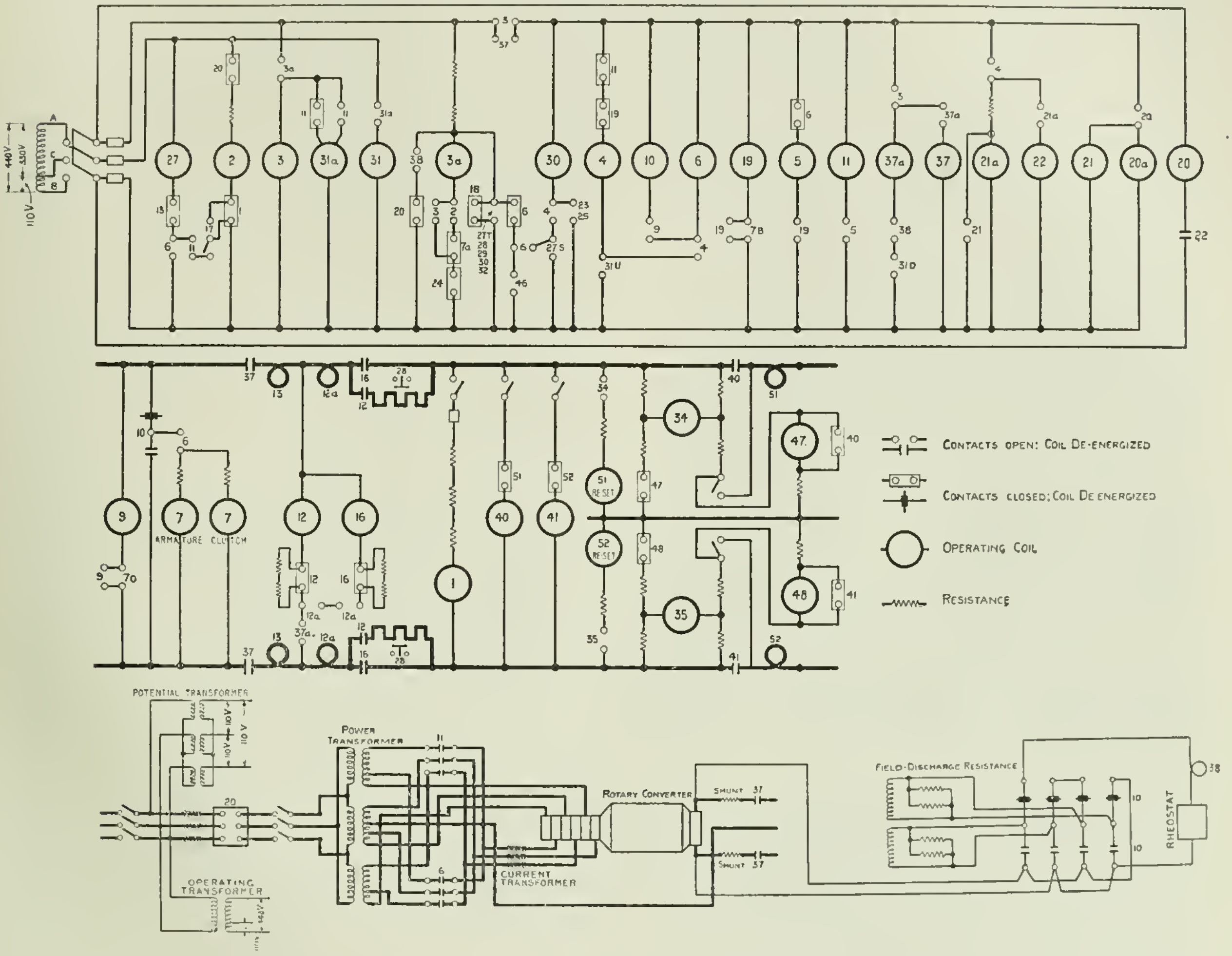
In the diagram on page 419 the connections are arranged schematically, the numbers corresponding to the description and operation of the individual apparatus.

The automatic operation is started by means of a low-voltage d.c. relay (1), which operates to close its contacts when the voltage on the d.c. busbars drops to a predetermined value due to the line voltage-drop consequent upon a certain demand for power. When the contacts of relays (1) are closed they insert, through an interlock on the main oil circuit-breaker (20), the operating coil of an a.c. voltage relay (2). This relay has a time-lag of a few seconds and its function is to prevent the station starting due to a sudden drop in the d.c. network voltage, and also to prevent the station from starting when the a.c. voltage is abnormally low. When the contacts of relay (2) are closed they establish a circuit through the master relay (3a). The contacts of relay (3a) are then closed and complete a circuit through the operating coil of relay (3) which completes the closing circuit of (3a) to hold it in.

The contacts of relay (3a), when closed, also complete the circuit, through an interlock on the running contactor (11) of the operating coil of relay (31a), to cause its contacts to close and start the small motor of the brush-lifting device (31). This motor, by means of gears and a crank, raises the d.c. brushes from the commutator. When the brushes have been raised to the full extent, a throw-over switch operated by a crank disconnects the relay (31a) and thus de-energizes the motor. The brushes now remain in the raised position until the circuit of (31a) is again completed by the closing of an auxiliary contact on (11), which closes when the contactor closes. This starts up the motor which actuates the crank to lower the brushes on to the commutator. The throw-over switch is returned to its original position by the crank, and is thus ready to repeat the above cycle of operations when the converter is again required to start.

In series with the operating coil of relay (3a) will be found the contacts of an overspeed device (24) and also a contact (7a) in the polarized motor relay. This contact (7a) is closed only when the relay is in correct working order, and is placed in series with the coil of relay (3a) so as to ensure that, before the station can start, the operating element of the polarity relay is in the neutral position. Shunted across the coil of relay (3a) will be found the contacts of a number of protective devices.

Relay (18) is an induction-type polyphase voltage and reverse-phase relay. This relay, by short-circuiting the operating coil of relay (3a), will prevent the starting of the converter if the phase rotation of the supply is reversed or if one phase of the supply is open. The remaining protective devices will be described later.



One main contact of relay (3) establishes the circuit for the main control busbar for the rest of the automatic apparatus. When the brush-lifting device is in the raised position it closes an auxiliary contact which completes the circuit, through interlocks on relay (19) and the running contactor (11) of the operating coil of a relay (4). One main contact of relay (4) completes the circuit of relay (21a) which in turn closes contactor (22). Contactor (22) completes the operating circuit for closing the oil circuit-breaker (20), an auxiliary contact on which makes a circuit through the low-voltage trip (20a) and also through the operating coil of the induction time-limit relay (21). Relay (21) has a short time-lag, at the end of which its contacts close and short-circuit the operating coil of relay (21a), thus causing the latter to open, which in turn opens contactor (22). The opening of contactor (22) breaks the circuit of the operating coil of the oil circuit-breaker (20) which is now held in the closed position by a mechanical latch.

The other main contact of relay (4) completes the operating-coil circuit of starting contactor (6), to cause the rotary converter to be connected across the starting taps of the transformer. The converter will now start to rotate, and when it is in phase with the supply the d.c. voltage will build up with either correct or incorrect polarity. This is indicated by the action of a polarized motor relay (7), which consists of a small armature mounted so that it can rotate between the poles of a fixed permanent magnet. The armature is energized from a pair of pilot brushes on the commutator, and thus its direction of rotation depends upon the polarity of the converter. Connected to the shaft of the armature through reducing gears and a clutch are two pairs of contacts, (7b) and (7d). If the polarity of the converter is reversed the armature will rotate and close contacts (7d), thus closing the field-reversing relay (9) which sets up its own hold-in circuit. The closing of the main contacts of relay (9) causes the operation of the field-reversing contactor (10). This contactor breaks up the converter field into two sections, connects them in parallel in the reverse direction and thus causes the converter to slip one pole. When the converter has slipped one-half of the polar position the d.c. voltage falls to zero and the field-reversing relay (9) opens. This allows the field contactor (10) to return to its original position, the converter then coming up with the correct polarity.

When the polarity is correct, the d.c. voltage will build up again and the polarized motor relay will rotate to close contacts (7b). When these contacts are closed they complete the circuit of the operating coil of the a.c. shunt relay (19) which makes its own hold-in circuit. An auxiliary contact on relay (19) opens the circuit of relay (4), thus causing all starting gear to be de-energized.

The main contact of relay (19) completes the circuit through an interlock on starting contactor (6) of the a.c. shunt relay (5), an auxiliary contact on which makes the battery circuit of the automatic voltage regulator. This relay (5) also makes the operating-coil circuit of the running contactor (11) which closes and connects the converter across the full voltage of the transformer secondary. The closing of running contactor (11) energizes, through an auxiliary contact, relay (31a), which in turn starts the brush-lifting motor (31) to cause it to lower the brushes.

A protective relay (38) is provided with its coil in series with the shunt field of the converter. This relay ensures that the field strength of the converter is adequate before any load can be taken. When the field strength has reached its normal value, a circuit is established through a contact on relay (3) through an interlock on the brush-lifting device (31), through the contacts of field relay (38) and through the operating coil of the auxiliary shunt relay (37a). Relay (37a) in turn closes the main contactor (37), which is in the d.c. converter circuit. Although the contacts of (37) are in the d.c. circuit, its operating energy is obtained from the a.c. circuit.

Another contact of relay (37a) completes the d.c. closing-coil circuit of the main d.c. operated contactors (12). This circuit, when closed, connects both poles of the converter to the busbars through limiting resistances. The d.c. accelerating relays, (12a) and (12b), measure the amount of load picked up and, if this is not excessive, allow contactor (16) to cut out the limiting resistances.

Should the converter during its operation become greatly overloaded, these accelerating relays will work in the inverse order and insert the limiting resistance to limit the load. If this load should persist, grid thermostats (28) will shut down the automatic equipment when the resistance grids reach approximately red heat. These thermostats will allow the station to start up again when the grids have cooled down.

The overload setting of the d.c. accelerating relays is purposely made very high to permit the full overload capacity of the converter to be utilized for short overloads. If the overloads should be of such magnitude as not to operate the accelerating relays, and should they persist long enough to endanger the windings of the converter, a thermal time-element relay (29) will shut down the converter and allow it to cool off. After such cooling the converter will again be put into service automatically. This thermal relay measures the R.M.S. value of the a.c. input to the machine. This is an accurate measure of the heating in the machine.

A d.c. reverse-current relay (32) is provided so that, if the a.c. supply should become inadequate while the machine is connected to the d.c. system, the converter will be disconnected from the line before the reverse flow of energy can damage it.

Induction overload relays (23) are provided which protect against short-circuits in the converter or converter leads. They also operate in case of a serious flash-over.

Thermostats are provided in each of the machine bearings, and, should any of these operate, a lock-out relay (30) is closed, thus taking the converter entirely out of service by short-circuiting the operating coil of relay (3a). This lock-out relay (30), whenever operated, must be reset by hand. An auxiliary contact is provided in the relay so that a signal circuit may be energized if desired. This signal circuit may operate semaphore or lights in front of the station, or send signals over a telephone or telegraph circuit to give warning of the trouble.

Relay (46) is an induction-type relay but of special construction so as to constitute an unbalanced phase-current relay. The relay coils are connected to the three current transformers in the low-tension circuits. During the starting operation the contacts of this relay are put in series with the operating coil of the lock-out relay (30) by an interlock on the starting contactor (6), and should any fault occur during the starting period the lock-out relay (30) is at once energized, thus closing down the entire automatic equipment. Normally, however, the trip contacts of relay (46) are connected across the operating coil of relay (3a) by an interlock on starting contactor (6) which closes when the contactor opens. Thus, should any trouble arise on the high-tension line while the converter is running, it will be shut down by master relay (3a) but will be left in condition to restart automatically as soon as the high-tension line is again in a satisfactory operating condition.

Each of the feeders is provided with magnet contactors, (40) and (41), which open in the event of an overload by the action of overload relays (51) and (52). When these overload relays open they are held in the open position by a mechanical latch and cannot be closed until the respective resetting coil, (51) or (52), has been energized and has thus released the latch. While in the open position the contactors are shunted by a measuring resistance bridge, the circuit to the mid-wire of the feeder being completed by a contact on (47) or (48) which closes when the relay (47) or (48) is de-energized. This occurs as soon as the feeder contactor (40) or (41) opens, since the operating coil of the relays is short-circuited by an auxiliary contact on the contactors which closes when the contact is open. The resistance bridge is now used to measure the resistance of the feeder. As the load on the feeder is reduced, the voltage-drop across the relay-shunting resistance increases until at a predetermined value the contacts of relay (34) or (35) close, thus completing the circuit of the resetting coil (51) or (52). When the resetting coil has operated, the closing-coil circuit of the contactor (40) or (41) is again energized and closes the contactor, thus restoring the feeder to service. The resistance bridge is disconnected from the neutral after a small time-interval by the operation of relay (47) or (48), which is energized through the opening of the auxiliary contact on the feeder contactors. The above arrangement is such that an overload on either of the outers will cause the respective feeder to be disconnected, and only reconnected when the overload has been reduced.

When the demand for power falls to a predetermined value under load, d.c. relays (13) operate to close their contacts and thus energize an underload delay relay (27). After an interval of time, which can be adjusted to be from 3 to 20 minutes, the time-delay relay closes its contact and short-circuits the coil of relay (3a), which opens and de-energizes relay (3). When relay (3) opens, it de-energizes all the a.c. operated contactors and also causes the main oil circuit-breaker (20) to open. The station is now ready to start up again when the demand for power causes the d.c. voltage to drop.

The sequence of operations described above is very quickly performed, the total time from the demand arising to the connection of the rotary converter to the line being seldom greater than 55 seconds, plus the time-lag on the relay. This is a great advance over manual operation, which necessitates synchronizing by hand.

The operation of the station has surpassed our expectations in that its behaviour has been almost perfect since it was first put on load, or rather, put itself on load.

Naturally, numerous adjustments to the relays, etc., have been necessary, but this has been to enable them to meet our conditions of working.

At this point it might be as well to consider in detail the control of the outgoing d.c. feeders, and to consider two possible requirements, i.e. to control a dead-ended feeder and an interconnector fed from another source of supply. With this end in view the reclosing mechanism was designed to be applicable to both.

The feeders are therefore protected with automatic reclosing contactors having overload and inverse time-limit relays. Auxiliary contacts on these contactors are arranged to connect measuring resistances across the feeder circuit when the contactor opens. In the case of a dead-ended feeder they measure the resistance of the system, and if this is above a predetermined value the contactor closes again. If it is not of the requisite value the contactor is prevented from closing; if at a later period the fault is removed, the contactors close and restore the supply.

In the case of an interconnector fed from another source of supply the contactors close only when the voltage of the interconnector has risen to a predetermined value. The operating relay is adjustable over a wide range, and any reasonable conditions can be met with the apparatus as installed.

Various artificial faults have been put on the plant for experimental purposes, but have all been dealt with almost uncannily.

The relays are of substantial construction and we do not anticipate that they will give us any trouble provided that they have reasonable attention.

The fact that we have put a second station in hand on similar lines to the one described rather points to our entire satisfaction. The author would point out that in the station described, arrangements were made to run the plant for traction purposes when desired, the automatic features functioning up to and including the rotary-converter d.c. contactors, following which is a hand-operated throw-over switch, which may be closed on either the lighting or traction busbars, as desired.

The traction feeders are controlled by hand-operated standard circuit-breakers and knife switches. As the station is on a tramway route which several times a year has to handle very heavy traffic, this arrangement is very useful, especially as the station is situated on the top of an incline.

It is of interest to refer to the problem with which we had to deal, and the cost comparison which influenced our decision.

The network between the two stations mentioned was laid at a pre-war cost of approximately £29 858, but as only 40 per cent was available for useful work, due to voltage-drop, a feed into the centre would enhance its value nearly three times. The following five methods were open to us:

(1) To change over the whole of the distribution in the area in question to alternating current, by connecting the d.c. mains across a split single-phase transformer. This would mean that only a single-phase supply would be available and that all consumers' d.c. plant, such as motors, etc., would have had to be replaced by a.c. plant.

(2) To replace the whole of the d.c. mains by a.c. mains, creating a new a.c. system and finally scrapping the d.c. mains; or else to superimpose on the area an a.c. supply. This would mean that there would be two systems in the same area, that the d.c. consumer would be restricted to his existing load, and that the capacity of the d.c. mains would remain at their present value, i.e. only 40 per cent.

The cost of the above methods, coupled with their obvious disadvantages, led to their elimination, and only the three following schemes were considered in detail.

(3) To lay new d.c. feeders from the existing stations to a central point of the system, the feeders to be of sufficient capacity to increase considerably the value of the system.

This scheme would meet the present difficulty but did not allow for further extension or of new distributors being laid down from the point where the feeders fed into the system.

(4) To erect a new building and equip it with manually operated plant with three double shifts of operators.

(5) To erect a new building and equip it with fully automatic plant requiring the occasional services of an inspector.

Alternatives (4) and (5) would allow for very considerable extension to the existing distribution system, as new distributors could be installed as and when required.

Whichever of the three schemes was decided upon, new buildings and plant would be required, as the present feeding stations were not large enough to allow of more plant being installed, and the existing plant was fully loaded. Therefore, in considering the comparative cost of the schemes, the cost of buildings, rotary converter, manually operated converter and feeder gear has been taken as being common to all.

Considering first the capital cost of alternatives (3), (4) and (5) and ignoring the items common to each, the following would appear to be a fair basis of comparison :—

(3) The cost chargeable is the value of the new cables required from Cobbs Quarry and Rice Lane, together with the cost of laying the same to feed into the network at the position chosen, namely £12 500.

(4) Over and above the cost of laying a short length of feeder out of the station to connect up, the cost would be nil.

(5) The cost of the automatic gear, over and above the cost of the manually operated gear, £1 795, and connecting up feeders as in (4).

No sum has been added in cases (4) and (5) for connecting up the feeders, as the cost would be very little and the annual charge less.

The cost of the high-tension cable in cases (4) and (5) was not taken into account, because in the particular case under consideration the high-tension cable was already in existence and passed the site chosen. In other cases this cost will, of course, have to be taken into account.

As regards the operation of the three schemes :—

(3) would require very little more attention than at present, as the stations were already staffed and inspection would be as hitherto; also the lighting would be only slightly in excess of the existing lighting. The cable losses were neglected; plant losses in converters, being common to all three schemes, were also neglected, so that the only charges on this scheme are the capital charges.

(4) would require three shifts of two men per shift, at £1 285 per annum. As this station would come within the routine of a general inspection, the cost of inspection was ignored. The lighting of the station would cost about £20 per annum, so that the total running charges would be £1 305 per annum.

(5) would require more skilled inspection and a consequently higher rate of pay than the manually operated station, but this would be more than balanced by the reduction in clerical work at headquarters, consequent on there being no weekly wages to be made out and paid to shift men.

The station lighting would be nil, as obviously it would not be required.

The maintenance in the case of all three alternatives has been considered as common to each, although the maintenance on scheme (5) might be slightly in excess of that on either scheme (3) or (4).

As pointed out above, three shifts would be required in the manually operated station (4) although possibly only working 50 per cent of its time, and on this basis station (5) operating on load for 12 hours and being idle for 12 hours per day, with units at 1d. for operation purposes, would cost £93 per annum for energy.

Therefore in this station we should have a capital charge on the excess of automatic over non-automatic gear, and also a running or operating charge of £93 per annum. This brings us to the following actual charges :—

| | | |
|---|---|---|
| (3) £12 500 at, say, 9 per cent .. | .. | £1 125 per annum |
| (4) Running charges .. | .. | £1 305 ,, ,, |
| (5) £1 795 at, say, 9 per cent = £162<br>Running charge = £93 | | £255 ,, ,, |

It would appear from the above figures that, taking the difference between (3) and (5), there would be a saving of £870 in favour of (5) and a difference between (4) and (5) of £1 050 per annum in favour of (5), which represents a considerable saving in the cost of units supplied from this station.

The energy required to operate the station is as follows :—

*When idle.*—At such times the operating transformer and also the d.c. low-tension feeder contactors, of which there are eight (the neutral switches not being automatic), are alive.

| | |
|---|---|
| Operating transformer .. .. .. | 275 watts |
| Eight feeder contactors at 180·5 watts each .. .. .. .. .. | 1 444 ,, |
| Total .. .. | 1 719 watts |

*When operating.*—At such times the operating contactors, in addition to the above, are all closed, making a total of 3 397 watts, and it was on the above figures that the operating cost of £93 was calculated.

In practice it is found that, although the voltage regulator keeps the pressure steady, it does not allow for a rise in pressure with increase in load, i.e. there is no compounding effect. This point in a manually operated station is taken care of by the operator, so that a contactor type of field regulator is being introduced, which is operated from the main ammeter shunts and which will automatically raise or lower the pressure 1 volt for every 100 amperes increase or decrease in load.

As stated above, numerous tests have been applied to prove the ability of the automatic gear to operate under faulty conditions, and its operation has been not only satisfactory but much more accurate and rapid than manual operation, the various relays being able to discriminate more rapidly than the human mind.

The author concludes with the hope that the information given, and the causes and considerations which led up to the decision of the Electricity Department to adopt automatic stations, may be of service and helpful to many engineers who may be hesitating as to the adoption of fully automatic stations.

The thanks of the author are due to Mr. H. Dickinson, the City Electrical Engineer of Liverpool, for permission

to publish the information contained in the paper, and to Mr. L. Breach for his valuable assistance in the preparation thereof.

## APPENDIX A.

### Relays used in the Operation of the Station.

(1) Under-voltage relay.
(2) Low-voltage and time relay.
(3), (4) and (5) A.C. shunt relays.
(3a) A.C. shunt relay.
(6) A.C. starting contactor.
(7) Polarized motor relay.
(9) Field-reversing relay.
(10) 4 P.D.T. field contactor.
(11) A.C. running contactor.
(12) to (16) 1 250-ampere "C.B." contactor (line and resistance shunting).
(12a) D.C. accelerating relay.
(13) Series underload relay.
(17) 1 P.D.T. knife switch.
(18) Low-voltage and reverse-phase relay.
(19) A.C. shunt relay.
(20) Main oil circuit breaker.
(20a) No-voltage release.
(21) Low-voltage and time relay.
(21a) A.C. shunt relay.
(22) 125-ampere contactor.
(23) A.C. overload relay.
(24) Overspeed device.
(25) Bearing thermostat.
(27) Underload delay relay.
(28) Grid thermostat.
(29) Thermal time-element relay.
(30) Lock-out relay.
(31) Brush-lifting device.
(31a) A.C. shunt relay.
(31d) Brushes down.
(31u) Brushes up.
(32) D.C. reverse-current relay.
(34) and (35) Measuring relays.
(37) D.C. line contactor.
(37) A.C. shunt relay.
(38) Field-current relay.
(40) and (41) Feeder contactor.
(46) Unbalanced phase-current relay.
(47) and (48) Time-lag opening relay.
(51) and (52) Overload relay.
(64) Automatic voltage regulator.

## APPENDIX B.

### A Short Description of the Principal Relays used in the Operation of the Station.

(1) *Under-voltage relay.*—This is a simple solenoid-and-plunger type of relay in which, when energized, the plunger is drawn up into the coil. This plunger is connected at one end to a pivoted arm with a contact on the other end. The weight of the plunger is partially counterbalanced by a coil spring attached to the opposite end of the pivoted arm. This spring is used for adjusting the voltage at which the relay is required to operate. This type of relay is very sensitive and responds to slight changes in voltage.

(2) *Low-voltage and time relay.*—The main feature of this relay is to provide a short time-interval between the closing of contact (1) and the operation of master relay (3a). It is of the induction type and operates from a single-phase circuit. An aluminium disc is mounted in the air-gap between the poles of the laminated core. The shaft of this disc carries one of a set of contacts, and when the relay is de-energized these contacts are held open by a spring which rotates the disc until the movable contact strikes the top. When the relay is energized the torque overcomes the tension of the springs and the disc rotates until the contacts close. The movement of the disc is retarded by the damping effect of the disc as it moves between the poles of a strong permanent magnet. The time setting of the relay is changed by altering the position of the adjustable stop, which either shortens or lengthens the arc through which the disc must rotate before the contacts are closed. This time is adjustable from zero up to a few minutes. The construction of the relay also makes it a low-voltage relay, since, if the applied voltage is too low, the resulting torque will not be sufficient to overcome the pull of the spiral spring and the disc will not rotate.

(7) *Polarized motor relay.*—This is a d.c. motor-driven relay, the armature of which is connected to the converter pilot brushes. The field is produced by permanent magnets. The motor drives the armature of a magnetic clutch through a series of reduction gears. When the clutch coil is energized, the clutch solenoid housing, which is mounted loose on the shaft, is drawn along until it engages with the clutch armature. Attached to the outside of the housing is an arm carrying the movable contacts. A spring mounted on the shaft keeps the clutch housing normally in such a position that this movable contact is held midway between the stationary contacts (7b) and (7d). The clutch coil is connected in parallel with the motor armature so that it engages and disengages simultaneously with the starting and stopping of the motor. When the proper voltage is applied to the motor it will start in the direction dependent upon the polarity of the armature circuit, and the clutch housing with the movable contacts will turn until contact is made with either (7b) or (7d), the top and bottom contacts. Immediately after the clutch relay is de-energized the clutch disengages and the spring returns the clutch housing to the mid-position. Contact with the clutch coil is made by two small fingers. Another set of fingers (7a) is bridged by a contact strip on the clutch housing when this is in the mid-position.

(18) *Reverse-phase, open-phase and low-voltage relay.*—This relay is very similar to relay (2) except that it is a polyphase instrument. The relay is connected in the circuit so that with normal phase rotation the contacts are held open against the tension of a spiral spring by the torque of the disc. If the phase rotation is changed, the torque will also be in the opposite direction and the contacts will be closed. Also, if an open phase occurs no torque will be exerted. Therefore

a spring will rotate the disc and close the contacts. If the voltage drops below a certain value (usually 80 per cent) the torque will not be sufficient to overcome the effect of the spring when the contacts are closed.

(21) *Time and low-voltage relay.*—This is an exact duplicate of relay (2).

(23) *A.C. overload relays.*—These are the standard induction-type overload relays, and their construction and principle of operation are very similar to those of relay (2), except for a few minor details. The relay is single-phase and the element is wound with a current coil instead of a potential coil. A number of taps (usually 6 or 8) are taken off the small current transformer and brought up to the terminal plate on the index scale. This gives the different current values at which the relay will operate and close its contact. The relay has an inverse time-element up to a certain percentage of the operating load, but for greater currents the minimum time required to close the contacts is practically constant.

(25) *Bearing thermostats.*—These consist of copper bellows connected through a small copper tube to a bulb which is embedded in the lower half of the bearing, where it will be subject to the maximum bearing temperature. The bulb and the bellows are partially filled with a liquid which vaporizes at a given temperature. When the bearing reaches this temperature the bellows elongate owing to the pressure of the vapour, and the contacts are closed, and they remain in that position until reset by hand. Thus, in addition to tripping the lock-out relay, the inspector will have a positive indication as to which bearing was hot. The thermostats operate at approximately 90° C.

(27) *A.C. underload delay relay.*—This is a motor-operated relay and consists of a small induction motor driving, through a spur-and-worm gear reduction, a disc which carries a moving contact. The function of the gearing is to provide a long, definite time-interval between the starting of the motor and the closing of the contacts. Intervals of from 3 to 30 minutes may be obtained. In addition to the slow-closing contacts (27T) there is a second set of contacts (27S) provided, which close momentarily at approximately $1\frac{1}{2}$ minutes after the motor starts to revolve. These are the starting protective contacts which lock the station out if it fails to start within a given length of time.

(28) *Grid thermostats.*—These are practically the same as the bearing thermostats, the only difference being that they operate at a higher temperature. They will reset again as soon as the thermostat cools.

(29) *Thermal time-element relay.*—This consists of a number of bimetallic springs attached to a shaft which carries a movable contact. Current from the secondary of a current transformer in the low-tension side of the power transformer is passed through the bimetallic springs and heats them. The springs tend to unwind and in so doing the shaft is rotated and the contacts close. The element is mounted in a heat-insulated case which is filled with oil. The relay follows very closely the heating of the machine and is very efficient in protecting the converter from damage due to overheating. Mounted in the same case is a low-ratio transformer which gives the correct current in the relay, so that it will operate at the most satisfactory point on the calibration curve.

(30) *Lock-out relay.*—This relay has two pairs of contacts and a contact bridge which can make contact across either the lower or upper pair of contacts. In the normal position this contact bridge is latched so that the circuit is closed through the lower set of contacts. When the operating coil is energized the latch is released and a spring moves the bridge until it connects the upper pair of contacts and interrupts the circuit through the bottom pair. Once the relay has operated it must be reset by hand. A small target indicates white when the relay has operated.

(31) *Brush-lifting device.*—This consists of a motor connected through reduction gear to a brush-lifting ring on the converter. A jack-shaft carries four cams which operate four contactor switches. Two of these are limit switches which stop the motor when the brushes are in the correct position, either up or down, and the other two are interlock contacts, one of which prevents the converter from starting until the brushes are up and the other prevents the line switch from closing until the brushes are down. The motor is of the clutch type and does not pick up load until it is almost up to full speed. It is a single-phase motor and the split phase is used in starting.

(32) *D.C. reverse-current relay.*—This relay operates on the moving-coil principle, and is very similar to a millivoltmeter, except that all the parts are heavier and more robust. The relay is so connected that it will close its contacts only when current flows in the reverse direction.

(34) and (35) *Measuring relays.*—These, in connection with a suitable bridging resistance, automatically measure a short-circuit on the feeder when the breaker trips and determine when the conditions are such that the current will not be above a predetermined value when the breakers reclose. The relays are very sensitive to changes in current and are capable of very accurate adjustment.

(46) *Phase-balance current relay.*—This is used to protect the converter against running single-phase. Relay (18) will only prevent the machine from starting up on a single-phase, and in the case of phase failure while the converter is running it would continue to run on single-phase and act as a phase converter and supply three-phase potential which would hold the contacts of relay (18) open. However, with relay (46) in the circuit it will operate when the phase failure occurs, and shut the station down. Then, if the trouble is on the high-tension side, relay (18) will close its contacts and prevent the station from starting until the three phases are normal. If the trouble should be on the low-tension side, relay (18) will not operate, and the station can start up again. As soon as it attempts to start, relay (46) operates again. During starting the contacts of relay (46) are connected in the lock-out relay circuit, so that the station would then be locked out. This is a special polyphase induction-type relay and is operated from the secondaries of the current transformer in the low-tension circuit. If an unbalanced load, such as a phase failure, occurs, the torques produced at the different elements will not be the same and the relay contacts will close.

## Discussion before The Institution, 1 February, 1923.

**Mr. B. Welbourn:** The subject of the paper interests, I think, three sections of the industry, first, operating engineers, many of whom are now troubled with overloaded low-pressure networks; secondly, cable makers; and thirdly, plant manufacturers. I dismiss the cable makers very briefly because they have nothing whatever to lose in the average case, which will require high-pressure feeders. The author's case is a special one where high-pressure feeders existed. Other examples are to be put down and they must involve the use of more cable. I have watched the starting up of the Liverpool substation and on two occasions the rotary converter started up with the wrong polarity. The switches described by the author changed over very rapidly so as to correct the polarity. Last year I examined a fully automatic traction substation near Chicago. In that case the plant was made by the General Electric Company of Schenectady, and was supposed to be the last word in automatic plant. It behaved in the same perfect way as the plant at Liverpool, which is made by the Metropolitan-Vickers and Westinghouse Companies, but both appeared to contain some unnecessary apparatus. I can quite understand that manufacturers and operating engineers will all play for safety while they are launching an entirely new scheme, but I would ask them to combine to collect operating data so that they can determine after, say, five years' experience how much of this auxiliary apparatus can be eliminated, because this is very unlikely to be the last word in automatic substations. Statistics will inevitably show that certain risks can be accepted as good commercial risks. For instance, one would think that at this stage of the art it is hardly necessary to put thermostats on every bearing. I think that the author makes out a good case, from the commercial point of view, for the decision reached at Liverpool. The whole trend of practice at the present time is, in view of heavy labour costs, towards automatic devices. We now have automatic telephones, automatic lifts and so on, and I think that no one need be in any way afraid of the adoption of this principle, because past experience shows that the adoption of labour-saving devices brings more business and thus more work for labour. Up to the present all this fully automatic substation plant is of American origin, although not the whole of it has been manufactured in America. In that connection it would be of interest to know where our own manufacturers stand; for instance, whether they are ready for the considerable market which is sure to come. During the past few days an important order has been placed in one of our northern cities for automatic substations, and it is an open secret that the plant is being made in this country for a number of fully automatic traction substations. As Chairman of the Committee which is organizing the Liverpool portion of the Institution's Summer Meeting this year, I may say that this automatic substation will be thrown open for inspection, and I feel sure that it will prove to be the *pièce de résistance* in that city.

**Mr. G. H. Morris:** I also have seen the substation described by the author, and I agree with Mr. Welbourn that a reduction in the amount of auxiliary apparatus would be a very great advantage. During my visit the station was started up many times, the average time taken being about 44 seconds. When the rotary converter built up with the wrong polarity it took about 5 seconds longer, but generally speaking there was no fault to find in the sequence of operation. The paper states that the cost of attendants in a manually operated station would be about £1 200 per annum, but this figure is, I think, rather high. I notice that two attendants are allowed for on each shift, but I do not agree that is really necessary in a 500 kW station, and as this station is used on the peak load only I think that three shifts would be unnecessary.

**Dr. E. W. Marchant:** I, also, have seen the Liverpool substation in operation. The controls may appear complicated on paper, but the apparatus is very sound and strong and the station bears the stamp of good design, both electrically and mechanically. With regard to the increase in utilization of the mains which is brought about by increasing the number of feeding points, if one has a main of uniform section laid between two substations, and one assumes that there is a certain uniform demand for current along the whole length of the main, the maximum value of the permissible current demand is limited by the pressure-drop which is allowed. This, of course, in the case considered will be a maximum at the mid-point between the two substations. If now a substation is introduced at the mid-point between the original substations, the current demand that can be dealt with per yard of main, for the same maximum pressure-drop, will be four times as great. This may be explained, as the author has stated, by the fact that (1), owing to the distance from the substation to the point of maximum pressure-drop being halved, it is permissible to take twice as much current from the substation, and that (2), owing to the introduction of the substation, the number of feeding points to the main will be doubled. Up to the present, the only factor that has had to be taken into account in determining the maximum load permissible on the distributing system has been the pressure-drop, and the automatic substation described has been devised with a view to maintaining the pressure on the mains. When the feeding stations are sufficiently numerous, however, the extent to which the mains will be utilized will depend on their permissible heating. If a very large number of feeding points is introduced it is easy to see that the current density in the mains may be very greatly increased. In this connection it is interesting to note that there is a great advantage, from the point of view of heating, in laying a number of smaller mains in place of a few large ones. In the tests that we made in this laboratory with mains as laid by the Liverpool Corporation, we found that with a main of 0·1 sq. in. section the permissible current density for a temperature-rise of 20 degrees C. was 2 200 amperes per sq. in., whereas for a 0·6 sq. in. main and the same temperature-rise the permissible current density was only 1 000 amperes per sq. in. It would seem, therefore, that when heating is the predominant factor determining the limit of load that can be put on the system, it is desirable to use a number of mains of comparatively small section, in place of a few very heavy conductors. On economic grounds the case for the automatic substation has been very clearly made out in the paper, and there seems little doubt that, as time goes on, an increasing number of them will be employed on distributing networks.

**Mr. L. H. L. Badham:** In the installation described in the paper I notice that the machine is tap-started and fitted with a brush-raising device. This, however, introduces a large number of special devices. A method which appears to be less complicated is that employed in the 1 500-volt automatic rotary-converter substations in use on the Victorian Railways. The machines are started with the standard Rosenberg method of self-synchronizing. Each machine has also a small belt-driven d.c. generator mounted on the same baseplate, and this excites an auxiliary shunt winding on the rotary converter during the period of starting, thus ensuring correct polarity This small generator, however, is essentially to provide the necessary source of d.c. supply for the operation of the high-speed d.c. circuit breakers with which these machines are protected.

**Mr. W. M. Selvey:** We are enjoying, as a heritage of the past, a system of distributing electricity in a form which lent itself in the early days to the simplest and most rapid progress. To-day we have progressed so rapidly that difficulties have arisen, due to the rapidity of the progress. If we turn in another direction to consider the question of traction, the cost of a substation operator has become a very serious item in comparing the relative merits of a.c. traction and d.c. traction. There is no system of mechanism which cannot be improved; in fact, the machine has almost begun to eat the man. The protagonists of the d.c. traction system have produced first of all in America a machine which, as the author says, acts almost more rapidly and more precisely than the human brain. Therefore it is quite natural that when there are certain great immediate advantages to be gained one should adopt a complicated system of mechanism. The idea is not new; many years ago the problem was suggested to Edison, and after considering it very thoroughly he arrived at the conclusion that it was cheaper to employ substation assistants at 25s. a week. Let us consider a little more closely what the author is putting forward. He says, in effect: "I have a system here on which I have spent £20 000, and I am faced with the necessity of doing something more or less immediately. Therefore I can cast a balance sheet, to see which of three methods to adopt." In casting his balance sheet he takes, as the sole criterion, the utilization factor, which is, at present, only 40 per cent with the cables, but which he wishes to raise to a figure not stated. One of his main arguments for taking this as the basis is given in the first column on page 417, where he says: "The more extensive use of domestic apparatus has had the effect of raising the average load taken by consumers from ½ kW to 1 kW for lighting, up to 5 or 6 kW on the average when domestic apparatus such as radiators, cookers, vacuum cleaners, irons, etc., has been installed." I think that is the basis of the paper, and if that is so, by means of his automatic substation the author proposes to perpetuate a system of low-tension distribution. If he has already spent £20 000 on something which has produced ½ kW to 1 kW per head, what is he going to spend on cables if he gets this increased demand? Is he considering what he shall do to utilize the £20 000 worth of cables which he already has and get, let us say, 80 per cent utilization, which would make them worth, from his point of view, £40 000, or is he indirectly going to perpetuate a system which commits him to an expenditure of another £100 000 for cables, without first seeing what would happen if he had taken steps to superimpose an a.c. system? I do not suggest that he has arrived at the wrong solution, but I do suggest that perhaps he has not followed up fully the argument arising from his premises. It is a very serious thing, to my mind, if we are in any case committed to the perpetuation of a system of low-tension distribution. I am strongly seized with what appears to be the uneconomic expenditure on changing over, but I am still more strongly impressed by the difficulties that will arise if we continue to take a new load of heating and cooking on to the old distribution system. I am afraid we are getting very much into an impasse, and I suggest that any system of automatic substations must be properly confined to traction work where the system is direct current, and to those districts which seem to be fairly well saturated and in which there is not likely to be a five-fold increase of load.

**Mr. G. A. Cheetham:** The author is the first engineer in the country to have the courage of his convictions and to introduce plant into this country which has been used to some extent in America. A brief résumé of the history of the introduction of automatic apparatus into America would perhaps be not out of place. In 1914 the General Electric Company devised a scheme of automatically operating a substation, and they were the pioneers in that respect. They carried on for a few years along the lines they had originally designed, and introduced various improvements. Later the American Westinghouse Company also commenced to supply automatically-operated control gear for substations, but they carried out this scheme of automatic control in a slightly different manner. There are, of course, numerous ways of controlling substations; electro-pneumatic devices or cam-operated switches can be used. The American manufacturers thoroughly tested their scheme of automatic gear before putting it on the market, and that is a warning note that British manufacturers should bear in mind. After all, automatic operation is only a logical extension of the protective and control gear which we have had in this country for a very considerable time, and at last (because this gear has to be in operation daily) it is about to receive some attention in the way of inspection. The engineer hopes that protective gear will operate only on very rare occasions, and in consequence it is forgotten. For that reason many engineers have not a good word to say for it. It is essential that an automatic substation should be thoroughly inspected and that care should be taken of the gear if satisfactory operation is expected from it.

A device illustrating the simplicity of the gear, which in this particular instance is only used for the protection of a traction feeder, actually discriminates between a short-circuit and an overload. That at once suggests complexity, but it is really very simple. An ordinary a.c. transformer is put on to the d.c. main, and the rate of change of current instead of the actual value of the current is measured. A very simple device enabling the feeder to be disconnected immediately a short-circuit occurs, allows the feeder to remain on load to its full capacity in the case of an ordinary overload. With regard to the results of the operation of automatic substations in America, I propose to read a very brief extract from a report read before the American Electric Railway Engineering Association at the end of 1921. It is as follows: "From the operating records available it would appear that automatic operation is more reliable than manual operation. With any property, no matter how well trained the operators may be, there are certain errors of human judgment that must necessarily enter into the operation. In the large centres of population, where the tendency for high labour turnover is more pronounced, there will always be a larger percentage of new operators on the system than in some of the less active, smaller cities. This higher percentage of inexperienced operators will result in more operating mishaps, which are avoided by the use of automatic control. Where interruptions of the a.c. power supply are at all prevalent, the automatic control stands out conspicuously because of the speed with which service is restored." Altogether there are now 400 automatic stations operating in America. With respect to the change-over from direct current to alternating current, one point that is often lost sight of is the usefulness of a d.c. load in enabling a supply authority to keep up its power factor. If direct current is to be retained and utilized to its full advantage, and if copper also is to be utilized to its full advantage, the natural tendency is to distribute a large number of substations over a network at frequent intervals. In the past this has been impossible because of the operating charges, but we can get back to this idea when manual operating costs are reduced, and this is one of the chief advantages of the automatic substation. The automatic substation shows to its best advantage in the cost of control of a certain output distributed over a minimum number of machines. That will be apparent, as a full set of automatic gear is required for each plant unit. In a railway substation the elimination of the no-load running costs is important, especially on a railway where there are few trains running infrequently, as the station can be shut down between the times of running the trains. It should be noted, in addition, that the load efficiency of the station increases, because the station is not called upon to operate until there is some definite load for it. Automatic control is extending rapidly to the control of power stations, especially hydro-electric schemes, and in America many waterways are being harnessed which were previously considered impracticable because of operating costs. There is certainly a very large field of application abroad, and, to some extent, in this country, for automatic hydro-electric stations.

**Mr. F. G. C. Baldwin:** There are many points in the system described which are of interest to telephone engineers. Judging from what previous speakers have said there appears to be a certain impression that switchgear of the kind described may not be so reliable as manually operated apparatus. A problem that now presents itself to the engineer concerned with the distribution of electrical energy appears to be somewhat akin to one which the telephone engineer has had to tackle in the past 10 years, i.e. as to whether automatic apparatus will function properly, and whether the cost compares favourably with that of manual equipment. So far as the functioning of the apparatus is concerned, I have no doubt at all that, whatever difficulties do arise in regard to design and operation, those difficulties will be surmounted. Such has actually been the case with automatic telephone devices. Experience in telephone working is such that we can now rely upon automatic switches of all sorts to operate with unfailing precision and regularity. In Appendix A the author has given details of a number of relays used in the operation of the station. In telephone exchanges a very much larger number of such relays are used and they give practically no trouble in their operation. We also have thermostats, and machines which are started up each time a subscriber makes a call, and they perform their several functions admirably. The number of relays or similar devices associated with the system described in the paper is 64, while the number brought into operation during the course of one call in at least one automatic telephone system is largely in excess of that number.

**Mr. T. W. Ross:** I have been associated with the automatic substation question for the past three years, and I can assure those who suggest that the amount of apparatus should be reduced, that the scheme put forward by the author is the result of evolution which has taken place in America, and the amount of apparatus has been reduced as much as possible without impairing the reliability of the gear. The function of certain relays shown in the paper may not be quite clear to members. Certain relays in the scheme are really intermediate steps, and we find in practice that, especially in the more sensitive relays necessary for determining the sequence of operation, it is essential to reduce the current carried by the contacts to a minimum, and we have found that far more reliability is obtained by putting in an intermediate step. Although a thermostat may appear to some to be unnecessary, I can assure them that the thermostats used in this particular station and by other makers of this gear are a real engineering proposition. There is very little possibility of trouble arising when they are used. I agree that it is possible to install too much protective gear, but I believe that certain protective devices which are put into these substations are in themselves a very good insurance, and are worth the little extra cost involved. As regards reliability, I believe that with proper care the majority of relays are very efficient and cause very little trouble. I believe it is a fact that in America the question of starting has developed mainly along the lines of tap-started rotary converters, and I do not think there has been any serious trouble. To my mind, it is a pity to spend money in putting on the end of a rotary converter a pony motor which is only used to start up on occasions. The bogey of tap starting in the past has been the amount of power taken from the mains. Many electrical engineers do not object to putting a 500 h.p. induction motor on the mains, but they appear to think that a tap-started rotary converter will shut the station down every time it starts up. The rotary converter with the present damping arrangement takes very little current in starting. I believe I am correct in stating that a tap-started rotary converter does not average more than 60 per cent of the rated kVA load, and with the present large systems the kick is not felt on the mains at all. With motor-started rotary converters there is no need to raise the brushes, but brush-raising is quite a simple and sound mechanical job and has, to my mind, certain advantages. The brushes are raised by means of a small rod operating on a projection of each brush, which ensures that the dirt which collects there is loosened every time the operation is performed, and that is a decided advantage. I think that those who have had experience with tap-started rotary converters will bear me out that there is no difficulty in regard to the bedding of the brushes. The question of the fixing of polarity has been raised, but I should like to ask what is the good of installing an auxiliary exciter to fix the polarity of the converter when this can be done in 5 seconds by means of a simple, small, mechanically sound relay. The method of pole-slip described by the author is absolutely sure. Are these auxiliary exciters really worth while adopting? This question of automatic substation control seems to me to have evolved along the lines of automatic telephone exchange control. A certain automatic telephone company have stated that with 196 000 calls there were only seven mistakes. This result is obtained with comparatively delicate relays, and for automatic substation gear, which is much more robust and equally well protected from dust and dirt, we should expect a very much smaller percentage of error. I am quite sure that the automatic substation is a commercial proposition.

**Mr. P. J. Robinson** (*in reply*): Several speakers have referred to the large number of relays required to operate the plant. This number is, of course, based on the experience gained in automatic operation, and relays have been added from time to time as occasion has arisen. Possibly with more experience some relays may eventually be eliminated. If one is prepared to take risks, relays can be cut out, but as they are of sufficiently sound construction as to be no danger in themselves, it appears wiser to install the relays, the extra cost being an insurance against breakdown. The author is of opinion that bearing thermostats are essential. The estimated cost of operating the station manually has been criticized. This is high at the moment, but as two men are always employed per shift in Liverpool, the cost is determined by the trade-union rates governing a station of a specific capacity. With the present hours of running, two shifts could do the work, but having regard to future requirements three shifts should be allowed. Only 500 kW is installed at the moment, but the station is laid out for extension. The relative advantages of tap-started and self-synchronizing rotary converters are outside the scope of the paper.

Dr. Marchant referred to the heating of mains and suggested a number of small ones run at a higher density. I am afraid that the voltage-drop along these mains would prohibit their use.

Mr. Baldwin stated that more automatic devices are used in an automatic telephone call than in starting up an automatic station; as such devices are necessarily more delicate and used more frequently in the former, it argues well for the safety and satisfactory operation of the station.

Mr. Selvey mentioned the perpetuation of a system of low-tension distribution. It is not quite clear what is meant by this, because whether a.c. or d.c. the distribution system must still be low-tension, and when it is suggested that the average load under certain conditions has gone up from $\frac{1}{2}$ kW or 1 kW to 5 kW or 6 kW the diversity factor of the loads must be taken into account; the former which was purely lighting had a low diversity factor, whereas the latter which is domestic power has a high diversity factor, so that it does not at all follow that the load on the system will increase 5 or 6 times. The actual utilization factor was increased from 40 per cent to 118 per cent, so that the value of the cables was apparently increased from £20 000 to £59 000. Taking a figure, given by Mr. Gillott in his recent paper on "Domestic Load Building," of 65 kW installed and 19 kW actual loading, it is easy to deduce the increase in connected load possible with the above increase in the utilization factor; it appears that about 6·6 times the present observed load could be added before the cables already laid down at a cost of £20 000 would be fully loaded. Thus it seems that a long life has been added to the existing d.c. network without further appreciable expenditure on mains. If at a later date we are forced into relieving this district by other methods, the expense involved will not be much greater than that entailed at the present time.

## North Midland Centre, at Leeds, 6 February, 1923.

**Mr. W. E. French**: I had some difficulty in understanding the schematic drawing, but the author's explanation of the diagram has made clear to me the operation of the station. The rotary converter appears to be amply protected both with regard to time and overload by contactor (16), and the grid contactors (12) and (12a); the latter are called accelerating coils and appear to be selective relays, which do not allow the rotary converter to come into action should the load be excessive. Do contactors (40) and (41) constitute an additional protection of the converter, or are they an overload protection of the mains as well as a safeguard against an excessive out-of-balance current on either side of the three-wire system? In the latter case their action is, I suppose, instantaneous. In this, as in other schemes for automatic substations, tap-started rotary converters have been employed. I should have thought that the tap-started converter possesses, from the starting point of view, nearly all the disadvantages a machine for automatic substations could have. First, there is the heavy starting current which such machines demand, corresponding to about 50 per cent of the normal kVA of the rotary converter, with just enough torque to start the machine. Secondly, there is the fear of such tap-started converters coming in with the wrong polarity. Thirdly, owing to the fact that the converter has to start in its own armature field, there is a rotating potential curve with regard to the brushes, resulting in considerable sparking; hence the need of the brush-lifting device. From my experience I should consider such a device to be undesirable and a weak link in the chain. This view is borne out by some records published by Mr. C. H. Jones, Chief Engineer of the Chicago-Milwaukee Railway, who states that about 20 to 25 per cent of all the failures to operate of the automatic substations on his system have been due to the brush-lifting devices. I should have thought that rotary converters started on similar lines used for automatic synchronizing, or cascade converters, would have been distinctly preferable, because they not only avoid all the troubles mentioned but materially reduce the number of control relays and apparatus, simplify the plant and so ensure an easier control of the substation and the d.c. voltage on the distributing mains. As a matter of fact, the cascade converter offers a d.c. machine which can be designed for a frequency lower than that of the supply, and hence advantages of operation and commutation accrue, which machines not constantly under supervision should essentially possess. In the *General Electric Review*, 1918, Mr. Davies deals with five automatic substations, considering two cases for electric traction work. In the first case the trains are running with a 2-hour interval; in the second with a 1-hour interval. The output of the rotary converters in each substation is 300 kW, the daily service is 18 hours and the daily consumption 1 530 kWh in each case on the d.c. side, corresponding to an intake of 1 860 kW on the three-phase side. The total service of all five substations is 90 hours; the standstill period with the 2-hour service is 60 hours, and with the 1-hour train service 38 hours. The no-load consumption of a non-automatic station is given as 15 kW in each case. Therefore, the saving for the automatic station in the first case is 900 kWh, and in the second 570 kWh, corresponding to an annual saving of 328 000 kWh and 208 000 kWh respectively. The daily consumption of a non-automatic station is 2 760 kWh for the 2-hour service and 4 290 kWh for the 1-hour service; this gives a saving of 32·5 per cent and 13 per cent, respectively. These figures point to the conclusion that the instalment of automatic substations for power and lighting service, where the rotary converters are required for a considerable length of time and where the period of idle running of the machines is relatively small, would be a mistake. I do not incline to that view. The problem is rather one of economy of feeders and distributors. The installation of many rotary-converter substations of relatively small capacity must produce such an economy and therefore materially relieve the total operation cost of the whole system. The full extent of such benefit can be experienced only by the use of automatic substations, which eliminate the heavy charges due to personnel. In addition, any reduction of running charges due to avoidance of idle working of the rotary converters is all to the good.

**Mr. J. W. J. Townley**: The author has explained that this automatic substation has been put in to develop to the fullest possible extent an existing d.c. network. He has considered several alternatives to the existing d.c. system and, to judge from the map which he showed on the lantern slide, he appears to have adopted the best solution of his particular problem, as the conditions are ideal for an automatic substation. He has on either side a manually operated substation, and presumably this automatic converter plant is intended for use on peak loads only. I am inclined to think, however, that the automatic substation will not be developed to any very great extent in this country except for traction work, because if one takes a long view it will usually be found that it is much better to face at once the expense of changing the area to a.c. supply, or, as is being done in several large undertakings, to superimpose an a.c. network on the d.c. system and gradually supersede the d.c. supply. Bearing in mind that the cost of an automatic substation is fully six times that of a static substation of the same output, it will be apparent that a considerable sum is available for the cost of changing-over the system. The automatic substation for general supply networks can only be looked upon as a temporary expedient to prolong the life of existing d.c. networks and for installation in relatively small units. I can hardly imagine the circumstances that will justify an automatic substation containing, say, six 1 000 kW rotary converters. For a substation of this size the cost of attendance is not a great proportion of the total running cost, and I am inclined to think that the manually operated substation will be retained for such sizes. There are certain cases where a partially automatic substation would be desirable, and I have such a substation in mind upon the undertaking with which I am connected. It is a traction substation containing a single unit, and but for the operation of the line circuit breakers there would be no need for an attendant during the time the plant is running. The rotary converter is started up at the same time each morning and shut down at practically the same time each evening. This could be done manually, and with thermostats fitted to the bearings and automatic reclosing circuit breakers such a substation could be run without any other attendance than that required for starting up and shutting down. The capital cost of a semi-automatic substation should be considerably lower than that of the fully automatic plant described, and the existing converters could be used. I have no doubt that some of the apparatus shown will in the future be dispensed with, one of the first items being probably the brush-lifting device. I have recently inspected some tap-starting rotary converters of 500 and 1 000 kW. These machines were started up direct from the a.c. side without the d.c. brushes being lifted. There was no excessive sparking at the commutator and the running up was entirely satisfactory. The actual time taken in the case of the 500 kW set from closing the switch to the rotary converter being in synchronism was 30 seconds, and the current taken was 35 per cent of full-load current. The elimination of brush-raising and brush-lowering devices will be one step towards simplification. From the published accounts of experience with automatic substations in the United States, confirmed by the author's account of his plant, it would appear that the fully automatic substation is a satisfactory proposal where the conditions are favourable, but the field for the automatic rotary-converter substation lies, I think, in traction work and not in feeding general supply networks, which should, wherever possible, be converted to a.c. supply. There are also many opportunities for the use of automatic gear in static substations, where automatic operation has not, I think, been developed to anything like the extent to which it will be in the future, or to the extent to which it is used on the Continent both for the switching-in and switching-out of transformers and for voltage regulation.

**Mr. R. M. Longman:** In the case cited by the author the automatic substation provided a good solution of the problem, the deciding factor being that the copper is already in the ground and is being used to only 40 per cent of its capacity. Where the copper is already loaded and where the load will increase, the conditions are entirely different; in this case the best solution would be to superimpose an a.c. distribution system. In large towns a site can generally be chosen near which are shops, offices and factories using a considerable amount of power. By adopting an a.c. system the network feeding the town is much relieved and will probably enable the remainder of the d.c. distribution to carry on for some considerable time. The author has calculated the cost of operation on the basis of three shifts of two men per shift. I have worked a substation containing more than 500 kW of more complicated plant than this, but with only one man per shift. I think that if this substation were manually operated only one shift of one man would be necessary during the load period, as there is a manually operated substation on each side of it. Possibly a second shift would be required for four or six months during the year. What is the nature of the load supply? The time of operation, viz. 45 to 55 seconds, is quite satisfactory, particularly for tap-starting, although Mr. Townley has referred to a case in which a rotary converter was put on the bars in 30 seconds. Are current transformers inserted on the E.H.T. side of the transformer to operate protective gear in the case of a failure of the transformer, or does the machine continue on load until shut down by a drop in the d.c. pressure? In the case of failure of any part of the gear and the plant shutting down, is there anything to indicate to the inspector on his arrival which particular item has caused the shut-down? It is of particular importance that the cause of failure should be discovered quickly, so as to enable the trouble to be rectified, if possible, and the machine put on load again. In the case of a fault occurring on some part of the machine, and the particular piece of apparatus which should have operated failing to do so, is there a second relay which may then operate and so shut the machine down? In other words, is there a duplicate line of defence? I agree with Mr. Townley that we have not given enough consideration to automatic regulation on either d.c. or a.c. systems.

**Mr. P. J. Robinson** (*in reply*): The author does not agree with Mr. Townley that automatic stations will only be developed for traction work in this country, as there are many instances similar to the one referred to in the paper, which Mr. Townley refers to as ideal. The statement that an automatic station will cost six times as much as a static station is not correct; the author would put it at a much lower rate than this; possibly twice. There appears to be no reason why the life of the d.c. network should not be prolonged (see my reply to Mr. Selvey in the London discussion). The question of tap-started rotary converters is dealt with elsewhere. No doubt, automatic gear will be introduced into static stations feeding into the low-tension system with a view to cutting down light-load losses in transformers.

Mr. Longman has asked if current transformers are inserted on the high-tension side of the transformer. They are shown in the figure on page 419 between the incoming isolating switches and the oil switch. They operate the protective gear as stated in the paper. It a fault on the plant has operated the "lock-out relay" a white disc shows on the relay and this calls the inspector's attention to several relays which alone can operate the "lock-out relay," viz. self-indicating bearing thermostats (No. 25 in the diagram), a.c. overload relay (No. 23), station not functioning in the time given it to complete its operation (No. 27 S), unbalanced phase at starting (No. 46). After overhaul, if it is not clear what has happened, the gear will be operated until it ceases to function, at which point the trouble will be located.

Mr. French asks if (40)–(41) act as protective gear to the converter. They do not directly, as they constitute the feeder protective gear. Their action is instantaneous. The figures which he gives regarding saving on automatic stations which have considerable idle periods are very interesting. They are in agreement with the author's conclusions.

## North-Eastern Centre, at Newcastle, 12 February, 1923.

**Mr. H. W. Clothier:** The author says that British engineers have fought shy of fully automatic control, so Liverpool appears to have taken a bold step. I suggest that it has been not so much shyness as cool calculation on the part of British engineers. It is not that they did not think of it. Nearly 30 years ago some automatic gear was designed for switching in and out banks of transformers for use in this town by the Newcastle and District Electric Lighting Co. It is almost as long ago that the remote-started and remote-controlled automatic substations were installed at Hull and elsewhere on a high-tension d.c. transmission system. At Hull to-day there are 20 fully automatic substations distributing direct current. Is it that the economy in putting down small d.c. substations has not been proved, or that in their wisdom British engineers have found greater economy in a.c. distribution? It cannot be for want of skill in the manufacture of automatic apparatus in this country. I am sure that there is no need to search America or Switzerland for designers and manufacturers of automatic electrical devices. There has, in fact, been a surfeit of them in this country; no sooner does one automatic device appear than others just as good, if not better, are produced. However shy the users may be, there is no shyness on the part of British manufacturers. I am not quite convinced that the cost comparison is correct. It seems to me that six attendants at £200 per annum is an extravagant use of men for running a little substation of 500 kW. In schemes (4) and (5) on page 422 the capital cost of the plant in not included. If the substations were made larger the proportionate cost of the attendants' salaries would go down and that of the automatic gear would go up. Has the author made comparisons over a broader range of plant capacity? I feel sure that there have been some good reasons for the comparative scarcity in demand for automatic substations in this country. Could anything be more demoralizing for two men than to sit in that little substation day in and day out with practically nothing to do but watch a few instruments and occasionally turn a handle? If only for their sake let us have the automatic substation. It may deprive a few of that monotonous prospective occupation, but it will cultivate a better type, a skilful operating engineer whose mind can quickly grasp a diagram and whose fingers are adept in the adjustment and connection of relays. The lot of an operating engineer will not be bereft of activity. As a test for the type of man, consider carefully pages 418 and 419, on which are given the sequence of operation of relays, contactors, auxiliary switches, etc. If a man can pass the point where the "converter will start" without heaving a sigh of relief, he is a very clear-minded man and a promising operating relay engineer. The expression "almost perfect" on page 421 shows that however little it may be there may be yet some improvement necessary and some work to be done. A good case may be made out for the use of motor converters in automatic substations in the future, due to the ease of starting-up and synchronizing. The crux of the whole problem is, of course, robust relays in distinction to instrument work.

**Mr. R. D. Spurr**: I agree with the author as to the utility of the fully automatic substation, but we have not, I think, quite appreciated its proper sphere of operation on a d.c. 3-wire network. Automatic substations were first used in the United States as booster substations for the purpose of maintaining a straight-line voltage on long lengths of suburban tramways, and by applying them in a similar way to large, straggling d.c. 3-wire networks we shall attain the desired result. At the present time many d.c. networks are, as the author states, loaded to 40 per cent of their full capacity and, owing to the demands for current in residential areas occurring at times which do not correspond to the usual industrial load demands, we are faced with an interesting problem in voltage regulation exactly similar to the problem solved in the United States by the automatic substation. Assuming a network supplied from several automatic substations as well as from a manually operated substation, the failure of the latter would probably shut the supply down altogether, but the failure of one automatic unit would not be seriously detrimental to anything, except that the voltage regulation would be bad until the plant was in service again. I feel sure that the voltage regulation as a whole would be better than it is with manual operation. The d.c. feeder switchgear seems to be very complicated. My experience has been that a good substantial fuse gives the best protection on low-voltage circuits; it has its own natural time-lag and is generally more reliable in every way than a circuit breaker which is very seldom used, never inspected and which, in consequence, fails to operate at the critical time. Three or more parallel d.c. feeders can be quite safely operated with fuses at both ends, and the chance of a faulty feeder not clearing properly is very small. The labour question with manual substations is an acute problem. In the majority of cases one man per shift is sufficient to operate the plant, and two shifts per day will allow the plant to be available when it is most wanted. In fixing upon one man per shift in a substation it must be understood that he confines his attention to operating the plant only, which can be and is done with perfect safety. Under no circumstances must the substation attendant be called upon to undertake any duties requiring the opening of E.H.T. cubicles; this should always be performed by an authorized person who is not a substation attendant or regularly employed as such. In most cases where an additional feeder is required it will be found that an automatic substation will cost about the same as the feeder, and a manually operated substation about twice as much. The automatic substation will supply the network with twice as many units as the proposed new feeder, and to make a manual substation a reasonably paying investment it must turn out twice as many units as the automatic plant. The losses in d.c. feeders are very seldom taken into account, but it will be found that with a long 0·5 sq. in. feeder never more than 50 per cent loaded, the actual watts lost are approximately equal to the total losses in a 500 kW automatic plant. The automatic substation will undoubtedly lengthen the life of many d.c. networks in residential areas and will enable them to meet the domestic loads which are gradually increasing.

**Mr. W. T. Dalton**: The author states that "it has been left to Liverpool to lead the way" in the adoption of the fully automatic control of substations. In 1920 the Newcastle Transport and Electricity Undertaking, when preparing designs for a traction substation in one of the outlying districts, provided for its fully automatic operation, but at this date prices had reached the high-water mark and the cost of the switchgear alone was £4 000 for 700 kW of plant, and as the substation was only to be worked on two shifts this figure was considered prohibitive. The scheme was therefore abandoned, not for want of confidence in the reliability of this form of control, but due to cost only. Has the author considered the use of telephonic communication between the substations and the generating station? It would appear that if suitable search coils, or a loud type of sensitive transmitters, were placed adjacent to the machines, with corresponding receivers at the supply end, continuous indication would be given as to whether the plant was running normally or otherwise, and short-circuits, or the noise from chattering brushgear as the results of a flash-over damaging the commutator, could be detected, thus enabling the staff to keep in constant touch with these unattended substations. Is there any provision for heating these substations? This may appear to be quite unnecessary, but will not some of the switchgear, if not protected against moisture due to climatic conditions, suffer in the course of time? The conditions in America are more favourable, the climate being much drier than it is in this country.

**Mr. B. H. Leeson**: Manual operation consists of performing a sequence of operations in such a manner that the plant is not subjected to conditions likely to damage it, and therefore the problem of designing an automatic substation equipment as an alternative is chiefly one for the switchgear engineer experienced in the design of protective apparatus. Automatic control should prove very efficient in running costs, particularly in the case of two or more machines, as the maximum output can be obtained from them, based on their thermal condition instead of by ammeter readings as in the case of manual control. Automatic equipment can discriminate where manual operation alone cannot. The automatic reclosing of a feeder circuit-breaker taking place only when its load will be within a prescribed limit is an example of this, and it protects the plant against unnecessary wear and tear. Protection for the machine against excessive overload, including short-circuit conditions, has received a great deal of attention by manufacturers of switchgear, and high-speed circuit breakers have been evolved and seem bound to take a very prominent position, particularly on traction schemes. The question of inserting resistance in the d.c. circuit to limit the output of the machine has been discussed at great length in the American technical Press, but I consider that its use on our systems will not be justifiable in many cases. I should like to have the author's opinion upon this question. The electrification of main-line railways offers a large future for the automatic substation. A typical scheme would consist of a chain of substations situated close to the track and fed from E.H.T. mains running alongside the permanent way. The d.c. feeder cables to the track would be short, as adequate protection to the machine against flashing-over troubles could be obtained by the use of reactance high-speed circuit breakers of the reclosing type. Thus a good voltage-distribution would be assured with a minimum cost of operation and capital expenditure on copper.

**Mr. T. W. Ross**: Some of the previous speakers have referred to converter substations in this country running unattended, but there is a decided difference between such substations and automatic substations. An automatic substation should do more than simply start, stop and parallel a rotary converter. The properly designed automatic substation should, in addition, be capable of anticipating any faults which may arise either inside or outside the substation, and of dealing with them more intelligently than the average operator. It is here that a fully automatic substation equipment differs from a so-called automatic substation, and intending purchasers would be well advised to study any scheme carefully and find out its limitations. The automatic substation was first developed in America. I have had the advantage of access to the inner history of its evolution and I would suggest that there is more in the design of these equipments than would appear at first sight. My company decided first of all to install an American equipment before launching out on our own designs. The experience gained has been very valuable and after exhaustive tests and experiments we now feel that we have perfected our own apparatus. I would strongly advise other manufacturers to try out their gear thoroughly before putting it on the market. To show the extent to which the automatic substation is being developed in America, I would mention one equipment which is being put into operation by the Westinghouse Company, in which 35 000 kW of rotary-converter plant is being controlled from a central office by means of automatic telephone relays. One pair of telephone wires connects the central office to each substation, and by using the ordinary telephone dial switch the machines can be controlled as required. This pair of telephone wires not only starts and stops the machines, but also indicates the load on each machine. The control engineer can thus see at a glance the load condition on the whole system and arrange to run his plant to the best advantage. This particular company claims that the increased distributing efficiency obtained is worth the large capital outlay.

**Mr. A. T. Robertson**: Arrangements are made to ensure that the converter has the correct polarity when supplied with current from the starting taps of the transformer, but there do not appear to be any provisions made to prevent the converter slipping a pole and so being unsuitable for putting on load during the operation of the relays between the opening of contactor (6) and the closing of contactor (11). Does the operation take place so rapidly that there is no possibility of a pole being slipped?

**Mr. P. J. Robinson** (*in reply*): With regard to Mr. Clothier's remarks, I have not attempted to prove that automatic switching has not been in operation for many years, for that point is indisputable, but there is a distinct difference between automatic control and fully automatic control. In the former the human element is the cause of the operation, whereas in the latter the human element does not appear except at its inception. The 20 stations at Hull come under the former heading. It is also indisputable that the first fully automatic stations were developed in the U.S.A., however much it hurts our pride to admit it. That we have engineers capable of improving on, and developing what has been produced is beyond doubt. As regards economy in a.c. distribution the paper deals with a particular d.c. area which was in existence, and does not suggest its adoption for new work. Mr. Clothier refers to the expression "almost perfect"; in this statement he is correct, for to accept any piece of apparatus as "perfect" is very foolhardy, and the author admits most readily that there is great room for improvement and a large field for investigation into the various elements which go to comprise a fully automatic station.

In reply to Mr. Spurr the question of fuses as against contactors received considerable attention, the contactors being decided on in view of the possibility of a temporary fault shutting down one section of the network permanently if fuses were adopted, and only temporarily if contactors were adopted.

It is interesting to note from Mr. Dalton's remarks that Newcastle contemplated a fully automatic traction station in 1920 and it is to be regretted that it was found impossible to carry the scheme through, as useful information would have been available to-day in regard to operating charges. As regards the heating of the substation, the operating transformer being situated under the high-tension cubicle is sufficient to keep it free from moisture. With this object in view, the transformer was put in the position stated.

The author appreciates Mr. Leeson's comment as regards collaboration between the engineer responsible for the lay-out of the scheme and the designers of the apparatus to be used. This is essential to obtain the best results, the engineer obviously not having all the sources of information at his disposal that the designer of a large firm of manufacturers can command.

If Mr. Robertson will refer to another section of my reply he will notice that the actual time required to correct the polarity is 4 seconds, i.e. the time of starting up if the polarity is correct is 41 seconds, and, if the polarity is incorrect and has to be corrected, 45 seconds.

## MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 19 FEBRUARY, 1923.

**Mr. J. S. Peck**: As I am not familiar with the actual details of construction of automatic substation apparatus, I shall not attempt to discuss the paper in a technical way. For a long time I have watched the development of the automatic substation in America. Some 18 months ago when I visited the United States, I took occasion to investigate the matter more closely. I visited several installations and discussed engineering features with the designers and found that both designers and operators were most enthusiastic as to the future of the automatic substation and the enormous developments which were likely to follow. After returning to this country it was arranged that an engineer from the Westinghouse Company should visit Great Britain in order to advise us as to the possible field for automatic substations here, and also to discuss the question with operating engineers in this country. This engineer, Mr. Wensley, succeeded in convincing many engineers here that there was a very promising future for the automatic substation, and I think he confirmed the opinions previously formed by Messrs. Dickinson and Robinson with regard to the advisability of installing such stations at Liverpool. In entering a new field where the apparatus is as complicated as is the case with the control for automatic substations, we deemed it advisable to take the fullest advantage of the experience gained by the Westinghouse Company, and the first equipments installed in this country were manufactured at Pittsburgh. Since then we have manufactured one complete equipment at Manchester and are now in a position to produce such equipment on commercial lines. We have thus been enabled to avoid many of the difficulties which are almost invariably encountered by any firm starting to develop a line of apparatus without having had previous experience in its operation.

**Mr. J. H. Williams**: I should like to ask the author whether the method of feeder protection with automatic reclosing contactors arranged by means of auxiliary contacts to connect a measuring resistance across the feeder circuit when the contactor is open, is as good as the alternative arrangement using a contactor which closes on a fault a definite number of times with a time-delay in between the closings and which is then locked out. The first method leaves the feeder always alive, a disadvantage on a traction system as the trolley wire is alive. We are actually fitting recorders on some of the automatic substations which we are installing, to record the operation of the various relays, etc., and we hope to get some useful information thereby. In one corporation system where the substations are worked with standard rotary converters and switchgear, the plant is started up and the substation run without attendants, and there has been practically no trouble. Automatic substations behave very much better than manual substations under fault conditions. Quite a number of automatic substations are now being manufactured in this country for tramway and railway load, and I do not think that the author is correct in saying that this is the only three-wire station in the world. I believe there are very nearly 20 in the United States. We do not like the method of starting up the rotary converter by means of tappings and a field-reversing relay and contactor, but prefer induction-motor starting with a separate exciter.

**Mr. S. E. Povey**: The use of automatic substations is particularly interesting from a railway traction point of view, as a means of reducing running charges. They appear to be applicable in certain instances, e.g. (1) on sparsely loaded sections; (2) to meet increases of load on existing sections; and (3) to meet loads during morning and evening rush hours. When used as on item (1), by shutting down the substation plant between trains the light-running losses are greatly reduced. With reference to items (2) and (3), particularly for suburban and inter-urban services, the traffic requirements demand almost twice the seating accommodation during the two morning and evening rush hours than during the remaining hours of the day. During these rush hours it is necessary to maintain the schedule speed because of the small headway between trains. Therefore in laying out a section due allowance must be made for the voltage-drop on the high-tension feeders, and particularly on the third rail, produced by these peak loads, so that the average voltage at the train is sufficient to enable the motors to work the train to schedule times. When these conditions are met it is obvious that during the light hours of traffic the system is under load. Again, even during " light traffic " hours, the large peak loads taken when starting a train, and not the average hourly load, in some cases govern the number of rotary converters which must be on load at a substation. The use of automatic substations will enable intermediate substations to be shut down during the " light traffic " hours without the average voltage at the train being too low to maintain the schedule, and by concentrating the load on a smaller number of substations the light running of all rotary converters will be greatly reduced. In the matter of control the subject appears to be quite different on a railway system than on a lighting and power system. On the latter the load is comparatively steady and the voltage on the network is not rapidly fluctuating. The minimum-voltage relay is therefore quite suitable for governing the starting up of the Walton or similar substations. However, on a traction system the heavy starting current causes large fluctuations of voltage on the third rail. While the operation of a voltage relay can be set to depend upon the average voltage, the train service is not symmetrical, and therefore the voltage control for starting an automatic substation does not appear to be fully suitable. The load on an electric railway follows the time table and is very definite and therefore, except in the event of the failure of an adjacent substation, the control of starting up and shutting down an automatic substation should be by time. Distant control from an adjacent substation would, however, appear to be advisable fully to cover the conditions. It is noted that the overload setting of the d.c. line circuit breaker is controlled by the " rate of rise in current value." I would draw the attention of designers to the heavy current taken in starting a main-line electric train, and would point out that the current taken on the first series or parallel notch may be from 1 800 to 2 500 amperes. The amount of current passing to a short-circuit will in some cases be less than these values. Again, I do not agree that the proposed method of measuring the resistance of the track before reclosing the d.c. feeder circuit breaker is satisfactory. The current taken by the brake pump motor, the heating and lighting of trains and stations, and the resistance of the fault, will have to be taken care of. It is not advisable to have any voltage on the track in such cases, as a motorman might have to carry out emergency repairs or adjustments near the third-rail shoes, etc. Also, the reclosing of a d.c. feeder circuit breaker three times before finally leaving it out is not to be recommended for a railway system. It would appear that because of important junctions, and when the train loads require the installation of three or four rotary converters, some substations will still require to be manually operated, and the d.c. feeder circuit breaker in adjacent automatic substations should be reclosed only when the voltage has been restored to the section by the manually operated substation. Automatic control of a substation equipped with two or possibly three machines would appear to be economical, but when four machines are installed manual operation is more economical. The possible economies by the use of automatic substations are to be welcomed as an item on the right side of the balance sheet when considering railway electrification.

**Mr. J. H. Collie**: Is it possible to use automatic substations on a railway system employing regenerative control? If so, what arrangements are made to keep the line open to receive the current generated by the motors during braking, which in some cases amounts, I understand, to 10 per cent of the power supplied, seeing that the substations would automatically shut down on the load being removed?

**Mr. G. E. Swift**: The paper disarms criticism in that it is purely a description of a fully automatic substation, and the fortunate circumstance of the substation being required on the route of the E.H.T. main no doubt went a long way towards the decision to erect a substation in preference to laying down more copper. As the substation has only recently been put into operation it is perhaps too early to describe and criticize it, but the fact that the installation operates with the discrimination described is most important. The substation has only one rotary converter installed, and having regard to the number of automatic apparatus it would appear essential to have duplication. If a second rotary converter were installed, and both were running on load, in the event of the load being reduced would one cut out or would both continue to run on divided load? If the substation has rendered idle a low-tension feeder, to what use will this be put? This would appear to have some effect on any basis of comparison. A comparison of the advantages to be gained by the use of automatic installations as against the laying down of additional copper would be welcome. It would appear that the conditions that a fully automatic substation has to fulfil do not obtain in many districts, and in many cases the consumers' habits are such that their requirements can be anticipated and met by a non-automatic substation with the usual protective devices, left to run without attention. Two such substations, each of 500 kW capacity, are in operation in Chester. They are installed adjacent to engineering works, the electricians of which start up and shut down the rotary converters when instructions are received by telephone from the generating station. These substations have been in daily use for over 12 months and have successfully met faults on both the a.c. and d.c. sides, while the operating costs for both do not exceed £50 per annum.

**Mr. P. J. Robinson** (*in reply*): It is very encouraging to learn from Mr. Peck that in future the apparatus required for automatic stations can be entirely produced commercially in this country and not have to be purchased abroad.

In reply to Mr. Williams, for the particular work required of the feeder contactors I think that the relay which discriminates between a bad fault and a high-resistance fault is to be desired. The fact that the feeder is alive is immaterial, as, of course, if the feeder fault has a low resistance the voltage on the feeder will be very small. If the voltage rises, then the fault has been removed and the contactor will close without delay and so restore the supply. If it is desired to work on the feeder, the control switch in the automatic station is opened and so makes the line dead. Stations which are started by hand and left on load must, of necessity, be very inefficient, owing to the light-load periods, and also it must be borne in mind that a large city may have many stations dotted about over large areas, which would make it very expensive to keep a staff for starting up and shutting down. I have referred elsewhere in my reply to the relative merits of tap-starting as against other methods of starting.

The majority of the comments made by Mr. Povey are outside the scope of the paper, but at the same time they are very interesting and instructive, and I have no doubt that all the points could be satisfactorily met in practice. It is distinctly worth noting that railway engineers regard automatic stations so favourably, both in this country and abroad, and I feel sure that in the near future there will be many operating on that class of work.

In reply to Mr. Collie, the station under discussion does not, of course, meet the case of regenerative control, but there appears to be no insuperable difficulty in meeting the case if it arises on railway work.

Mr. Swift is correct in his surmise that the E.H.T. supply being so near the centre of the load did help in the decision to erect a substation in the particular position chosen, but it did not materially influence the decision to erect a substation, as it would be a cheaper proposition to lay high-tension as against low-tension cables, which latter would meet the requirements only for the time being. The station is at present equipped with only one converter with automatic gear, but arrangements have been made for extensions in the future. The automatic gear will operate to cut in the second converter when the first is loaded up, and to cut it out again when one converter can deal with the load satisfactorily. The author has dealt with the question of stations started up and left to run. The two cases mentioned by Mr. Swift are not relevant to the point under review; obviously if one can get someone else to start one's station it is the cheapest method to adopt; also, the supply to, and the protection for, a bulk load must be dealt with in a different way from a general supply.

## SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 21 FEBRUARY, 1923.

**Mr. R. A. Chattock:** The author has described the difficulties that have to be met when a d.c. distributing network fed from a central station or substation becomes heavily loaded. I agree with him generally in the principle that has been applied at Liverpool to solve the problem. I should, however, like to suggest some other points of view which I think would tend to simplify and cheapen the proposition. The author states that only from 30 to 40 per cent of the copper in the long low-tension feeders is available, owing to the voltage-drop. He has surely overlooked the possibility of boosting at times of heavy load on the long feeders; by this means such feeders can be run up to 70 to 80 per cent of their capacity of 1 000 amperes per sq. in. I quite agree that a.c. four-wire distribution is simpler and cheaper to install from a distribution point of view; it is, however, not so good from the consumer's point of view. There is no stand-by possible, as there is with a storage battery in the case of direct current, and this is a most serious limitation in a densely populated and business centre. Again, alternating current is not nearly so useful for the small domestic motors, such as vacuum cleaners, washers, fans, etc. I quite agree, therefore, that Liverpool was wise to discard that way of overcoming its difficulties. Of the other three methods suggested, the laying of further d.c. feeders from the old or new centres is not justified when compared with automatically controlled substations. Where manual control is used, the high labour costs necessitate the installation of plant of large capacity. Automatic operation, however, allows the efficient use of plant in small units. The smaller the better, down to 50 or 100 kW, and this is where I join issue with the author. By adopting rotary converters for this purpose he has introduced what, in my opinion, are unnecessary complications. He is obliged to use units of plant of not less than 300 kW, owing to the high cost of the discriminating and protective gear, and this means that he must employ a certain number of d.c. feeders to get the output distributed in the network. In other words, he cannot quite approach the simplicity and cheapness of the a.c. system. I think that if he had adopted the plain induction motor-generator he would have greatly simplified the control though the efficiency would not have been so good. I think that this, however, would have been justified as such plant would cut in only at times of heavy load, and this effect would not be felt to any great extent. In order to approach the a.c. system, smaller units of plant are required, which can be installed at more frequent intervals and fed straight into the d.c. network. With a view to meeting this condition I have been experimenting with the mercury-arc rectifier. A 225 kW rectifier of the Brown-Boveri steel cylinder type has been installed across the outers of a d.c. network in the Harborne substation for about 18 months, and for the past 12 months has been working absolutely automatically, the substation being visited only about once a week when the apparatus is working alone in parallel with a storage battery. I should like to assure the author that there are other British engineers, notably in Birmingham, who are not afraid of automatic control. I am so satisfied with the behaviour of the mercury-arc rectifier that I have now installed two 25 kW automatic glass-bulb rectifiers of the Hewittic Electric Co.'s make across the two sides of another d.c. network. These are now functioning quite satisfactorily, and I am proposing to develop the supply to the outlying thinly populated districts in Birmingham by means of this type of apparatus arranged for automatic operation, i.e. it will cut out if the extra-high-tension supply fails, and cut in again when it is restored, faults on the d.c. network being controlled by fuses or circuit breakers. Such a system is directly comparable with an a.c. system, with the exception of the cost of the rectifier itself and a slightly larger substation building. Small substations can be installed wherever required to maintain the pressure over the network, and at times of light load certain of the substations can be arranged to cut out automatically. The necessary controls are quite simple, and are far less in number than the formidable list of 41 controls set out by the author in Appendix A as being necessary to control a rotary converter. I hope to be in a position shortly to describe in detail the controls that we have installed on our rectifier at Harborne.

**Mr. F. Forrest**: The author has not referred to the running hours of the automatic substation, nor the average load factor, so that we are unable to judge whether the choice of a rotary converter for use in this substation was justified. The rotary converter is the most difficult of all substation converting units to adapt for automatic control, but it is a highly efficient machine. If, however, the running hours are short, a less efficient machine which would require a cheaper automatic equipment for controlling it would be preferable. I presume that the rotary converter is a reactance-controlled machine, the voltage being varied by altering the field current. If this is so the question of power factor will become rather serious, as the author states that the machine is put into service when the voltage of the d.c. network is low, and this may coincide with a time when the voltage of the a.c. supply to the substation is higher than normal. Under such conditions the field current of the rotary converter would be reduced very considerably, and also the power factor. In fact the rotary converter working under such conditions may have a much worse power factor than the ordinary induction motor. The schematic diagram does not indicate how the change-over to traction supply is effected, but I presume that this is done by means of a tapping on the high-tension side of the transformer, which in turn will require a second extra-high-tension oil switch. The paper describes a highly ingenious arrangement of automatic relays which, however, because of their complexity will induce engineers to turn their attention to types of substation plant for automatic working which will necessitate fewer and simpler pieces of control apparatus, such as the induction motor-generator or the mercury-vapour rectifier.

**Mr. G. Rogers**: It is certain that with any type of automatic substation plant some risks have to be taken. The engineer who purposes to equip such substations must face these risks and assess them at their proper value. The failure of a fuse (of which I imagine there must be many to protect the various automatic relays) renders the plant inoperative and may involve a serious failure of supply. In cases where the substation is designed to feed into an existing network (such as in the case described by the author) or where there is a battery stand-by, the risks are minimized and can be faced with a greater degree of confidence. No engineer will install automatic converter substations for the sake of doing so; there must be a distinct saving of costs. In the case in point the author claims a distinct saving in the running costs, but it must be pointed out that in the case of the manually operated substation the total running charges of £1 305 given on page 422 could be reduced. In the case of a boosting substation of this type the machine would come into service only for the duration of the peak, which may be, if it is an industrial load, between the hours of 8 a.m. and 6 p.m., or, if purely a domestic load, on the evening peak only. In the latter case one shift only would be sufficient to operate the station, or, if the former, two shifts per day would meet the case. I should be glad if the author would give the total capital cost of this substation. I estimate that the cost of the rotary converter and the automatic switchgear was approximately £13·4 per kW. Automatic converting plant of the mercury-arc rectifier type could be installed for much less than this figure, i.e. about £8·9 per kW. I believe that there is a big scope for automatic substations for boosting purposes and for supplying outlying districts, but it will not pay to install them in cases where the supply can be given by means of new feeders run only from existing stations. Within a radius of 1 000 yards d.c. feeders could be laid to supply 500 kW at a total cost, including the boosters to enable full use to be made of the copper, less than that of installing an automatic converter substation such as described in the paper. I shall be glad if the author, in his reply, will give the following information: (1) The number of times per week it has been found necessary to visit the substation for inspection purposes; (2) the average daily machine load factor over 24 hours; (3) whether the converter can be started up by manual operation in the event of the failure of any part of the automatic switchgear; (4) whether there is any means provided to indicate outside the substation that the machine is in or out of service; (5) how the output from the station is measured, and what records are kept. Referring to Mr. Chattock's remarks and description of the automatic mercury-arc rectifier substation which we have had in operation for the past 12 months, I propose to describe the operation of this gear by means of a lantern slide, from which it will be seen that the arrangement is comparatively simple and involves the use of only 14 relays.

**Mr. W. E. Groves**: The ingenuity of the relay equipment of the automatic rotary converter substation must be admired, and, as the author testifies to its satisfactory operation, there is only left the question as to whether other means to the same end, involving less complex control, are not available. Such alternatives have been mentioned by previous speakers in the discussion. The smaller the amount of auxiliary apparatus necessary, the greater will be the range of application of the automatic substation from considerations of reliability as well as cost. It is certain that there is a very useful field for automatic substations to assist existing d.c. networks such as are dealt with by the author. Whether it will pay to employ them, as against laying down additional copper and feeders, is not difficult to determine. The author, however, neglects cable losses in making his comparison. This is hardly fair to the automatic substation, as these losses must vary inversely with the money spent in copper. It must therefore be assumed that he has made sufficiently liberal allowance in his estimates to justify such losses being ignored. The alternative of boosting has to be considered. This would be inadmissible except for dealing with peaks of short duration, and would not therefore apply to the 12-hour runs mentioned, but it is bound up with the question of cable losses. The author seems to suggest that he would have preferred to deal with the situation by substituting alternating for direct current, and his reasons for not doing so are convincing. In most large towns there is a zone where direct current is the right system because the loads are concentrated and direct current has certain advantages both from the consumers' and the distributors' points of view. Alternating-current distribution finds favour with the mains engineer because it reduces the liability to faults, and its adaptability to transformation must always commend it, but the development of automatic converting or rectifying substations will enable d.c. distribution to be extended into areas where this system would otherwise be impracticable, and the homogeneity of the supply system as a whole will be increased.

**Dr. C. C. Garrard** : I think that the author has made a very good case for the use of automatic substations for the purpose in view. I have inspected the installation at Liverpool, and I should like to congratulate him on the scheme and lay-out which he has adopted. It would be interesting to have a little further information regarding the grid. Could the author state the voltage-drop across this grid resistance with the full current passing through it ? As far as I can judge from the paper, the grid resistance is of very low ohmic value; such being the case, I fail to see how it limits the current from the substation in the event of a dead short-circuit. Of recent years the use of economy resistances in contactor design has been as far as possible obviated, and as the contactors used are operated by alternating current I should have thought economy resistances unnecessary. Their use seems rather a retrograde step. With reference to the extra cost of the automatic gear, which is given as £1 795, may one take this as being the minimum extra cost for the smallest possible automatic station ? I should also like to raise the question of the use of a tap-started rotary converter. I cannot understand why the latter has been adopted. The motor-started rotary converter seems very much more suitable for automatic operation. With the motor-started machine neither brush-lifting gear nor a pole-slipping device is required, as one can always rely on its synchronizing with correct polarity if auxiliary chokers are used. Its adoption would result in considerable simplification of the automatic switchgear. I should be glad if the author would state if there is any particular reason why a tap-started machine has been adopted. Also, it would be interesting to know whether the addition of a second or third rotary converter in the substation is contemplated when the load warrants it, and whether the automatic gear will deal with the problem of starting up one machine after another, according to the load demand, and shutting them down in a corresponding manner. In the upper portion of column 1, on page 421, the author states that the sequence of operations seldom occupies a time greater than 55 seconds, plus the time-lag on the relay, and that this is a great advance compared with manual operation, which necessitates synchronizing by hand. According to my experience, however, a self-synchronizing hand-operated rotary converter of this size starts up in less than half of 55 seconds. I do not mean by this, of course, to argue against the use of automatic gear under such circumstances as set forth by the author. The great point about the automatic gear, in my opinion, is that it saves labour charges, and renders the installation of substations economically possible in cases where it otherwise would not be.

**Mr. J. A. Cooper** : At a recent discussion before the South Midland Students' Section I was impressed by the number of members who had had experience of faults on protective devices. I should like to ask, therefore, if the author has experienced any faults on the relay apparatus, and, if so, how many. With reference to the Harborne substation, I suggest that it would be an improvement to fit a relay to the vacuum pump so that the rectifier vacuum might be kept always at its working value and no time be lost by pumping up before switching in.

**Mr. P. J. Robinson** (*in reply*) : In reply to Mr. Chattock, direct current certainly seems preferable to alternating current from the consumer's point of view, but for outlying residential districts, thinly populated, there appears to be no case for the former from the supply undertaking's point of view ; these districts if formerly supplied with direct current are changed over to a.c. supply and extended as such. With reference to the use of boosters, as the feeders in question supply a network at a comparatively short distance from the existing manually operated stations, the pressure at the feeding point would have been excessive, also extra converting plant and boosters would have had to be installed at the manually operated stations. The relative advantages of motor-generators or mercury-arc rectifiers, as against rotary converters, are rather outside the scope of the paper, but it must be borne in mind that a rectifier has a drooping characteristic, the voltage dropping considerably as the load increases, viz. 6·4 per cent from 25 kW to 300 kW, which is unsatisfactory ; also, as the vacuum pump has either to be kept running continuously or operated by remote control, the station is obviously not fully automatic.

Referring to Mr. Forrest's remarks, the converter is reactance-controlled, and no difficulty has been experienced with the power factor, which is as follows :—

| | |
|---|---|
| 200 amperes . . . . . . | unity |
| 400 ,, . . . . . . | 0·998 leading |
| 600 ,, . . . . . . | 0·995 ,, |
| 800 ,, . . . . . . | 0·995 ,, |

This is certainly higher than we should get from an ordinary induction motor. The transformer is provided with tappings on the high-tension side. For lighting or traction pressures these tappings are controlled by a throw-over switch, which is interlocked with the high-tension oil switch, any attempt to alter the position on load resulting in the latter switch being opened first.

In reply to Mr. Rogers, fuses are reduced to a minimum, and only the main fuses in the operating transformer circuit are in series with any of the operating relays. There is no battery as stand-by but the manually operated stations would act as stand-by in the case put forward. As regards the relative cost of a rotary converter with automatic switchgear and a mercury-arc rectifier with automatic switchgear, it is not clear on what amount of plant the figures given are based, as obviously both stations must be of the same capacity and provided with the same facilities; also the maintenance of one will greatly exceed that of the other, especially when the rectifier is of the glass-bulb pattern. The converter does its own balancing, whereas in a rectifier either a balancer or battery must be used, or else low-tension rectifiers in series, the latter, of course, being very inefficient.

In reply to Mr. Rogers's queries: (1) One visit a week is quite sufficient for inspection purposes, though more attention is being paid at present, until the inspectors are thoroughly conversant with the plant. (2) The average daily machine load factor, over 24 hours, is about 30 per cent. (3) The station cannot be started other than by the automatic gear, but in the event of any particular piece of apparatus failing this can be cut out and the station will still function automatically. (4) The "lock-out" relay is provided with special contacts for indicating externally that it has operated. These can be coupled to a red lamp outside the station, and instructions given to the police to notify the Electricity Department, or the contacts can be coupled to the private telephone wires, and give indication to the telephone operator. It has not been found necessary to adopt either of the above, as it is clear that the manually operated stations will be aware, owing to their increased load, that there is trouble. (5) The station is equipped with a recording ammeter and voltmeter, which are also an indication of the times of operating.

Mr. Groves mentions the use of boosters; this has been dealt with elsewhere. Cable losses were purposely ignored, as the case for the substation as against new feeders was strong enough without taking them into account.

Dr. Garrard refers to the use of economy resistances. These are only used on the main contactors (12) and (16) and the feeder contactors (40) and (41), which are across the d.c. bars; in no case are economy resistances used on the a.c. contactors. £1 795 represents the extra cost for a 500 kW converter and this amount would, of course, be reduced considerably with a reduced output, as obviously all main contactors, grid resistances, busbars, etc., would be smaller in comparison. The question of the relative merits of tap-starting as against other methods of starting, and also the starting-up of a second converter if installed at a later date, have been dealt with elsewhere in the reply. The grid resistance is provided as a safeguard to the station plant, the feeder protection taking care of a faulty feeder. If the manually operated stations failed, the load would become too heavy for the automatic station plant to deal with, and the grid resistance would cut in to limit the output. As it takes about 8 minutes for the grids to arrive at the requisite temperature to shut the plant down, the manually operated stations have a margin of time to get going again. The actual time required to put the converter on load is 41 seconds if the polarity is correct, and 45 seconds if the polarity has to be corrected.

In reply to Mr. Cooper, so far there have been no faults on any of the relays, nor does there appear to be any reason why they should occur. The relays are all of sound construction and very robust. Regarding the suggestion to fit a relay on the vacuum pump of a mercury arc rectifier, unfortunately this is a difficult matter which has not yet been overcome; it is, however, receiving very considerable attention.

# SOME PROBLEMS IN HIGH-SPEED ALTERNATORS, AND THEIR SOLUTION.

By J. Rosen, Member.

(*Paper first received* 10*th October, and in final form* 15*th December*, 1922; *read before* The Institution 15*th February, before the* Western Centre 5*th February, before the* Scottish Centre 13*th February, before the* North Midland Centre 20*th February, before the* North-Eastern Centre 26*th February, before the* North-Western Centre 6*th March, before the* East Midland Sub-Centre 10*th April, and before the* South Midland Centre 25*th April*, 1923.)

### Summary.

It is the author's purpose to present concisely some of the more interesting problems encountered, and the methods adopted to solve them. The problems, although encountered in high-speed alternators, will be found to be of interest to engineers engaged in other branches of the electrical engineering industry.

The following subjects are considered:—

(1) The history and failures of turbo-alternators.
(2) Mechanical construction of rotors and caps supporting the coil ends.
(3) Stator windings and insulation.
(4) Stator slots.
(5) Alternator ventilation, water cooling and the necessity for clean air supply.
(6) Exciter instability.
(7) Eddy currents in rotors.
(8) Oscillograph tests, in explanation of exciter instability, showing the necessity for precautions when breaking the main field by means of a quick-break switch without any discharge resistance.

### (1) The History and Failures of Turbo-alternators.

During the past ten years the development of large alternators running at high speeds has greatly advanced, and has brought out many interesting problems of design, construction, and operation.

Since the first steam-turbine-driven dynamo[*] (10 e.h.p., 100 volts, 75 amperes, running at 18 000 r.p.m.) was designed and constructed in 1884 by Sir Charles Parsons, engineers have recognized that high speeds of rotation are essential to direct-coupled, steam-turbine-driven machinery.

The velocity attained by a fluid when forced out of an orifice in the form of a jet is inversely proportional to the square root of the density, so that low density of working fluid implies high velocity of efflux from a nozzle. Also, theory and experiment prove that, to obtain good efficiency, the peripheral speed in a turbine must be comparable with the jet speed; so that, in turbines driven by steam, which has comparatively low density (only 1/140 of that of water at high pressure and 1/40 000 at 29 in. vacuum), the peripheral speed must be sufficiently high to obtain good steam economy. In practice, this means high speeds of rotation for the turbine and for the alternator, where the latter is direct coupled to the turbine shaft.[†]

The frequency for most electrification schemes in this country, however, is 50 periods per second, which limits the alternator speed to 3 000 r.p.m. Whilst this speed has been found suitable for moderate outputs, it is not sufficiently high to enable the best economy to be realized in small commercial turbines of 1 000 kW and below, a circumstance which has led to the development of geared turbo-alternators for these outputs.

Table 1.

*Parsons Alternators.*

| Year of installation | Output | Power factor | Speed |
|---|---|---|---|
| | kVA | | r.p.m. |
| 1909 | 1 250 | 0·8 | 3 000 |
| 1910 | 1 875 | 0·8 | 3 000 |
| 1913 | 2 060 | 0·8 | 3 000 |
| 1914 | 2 500 | 0·8 | 3 000 |
| 1917 | 3 750 | 0·8 | 3 000 |
| 1918 | 6 475 | 0·85 | 3 000 |
| 1919 | 7 500 | 0·8 | 3 000 |
| 1921 | 10 000 | 0·8 | 3 000 |
| 1922 | 12 500 | 0·8 | 3 000 |
| 1922 | 15 600 | 0·8 | 3 000 |
| 1922 | 18 750 | 0·8 | 3 000 |
| Under construction | 25 000 | 0.8 | 3 000 |
| 1911 | 2 140 | 0·7 | 2 000 |
| 1911 | 2 500 | 0·8 | 2 400 |
| 1911 | 3 200 | 0·75 | 2 400 |
| 1915 | 3 750 | 0·8 | 2 400 |
| 1916 | 14 700 | 0·75 | 2 400 |
| 1921 | 17 650 | 0·85 | 2 400 |
| 1909 | 2 860 | 0·7 | 1 500 |
| 1910 | 8 575 | 0·7 | 1 000 |
| 1913 | 13 150 | 0·95 | 1 500 |
| 1913 | 25 000 | 1·0 | 750 |
| 1915 | 19 000 | 0·95 | 1 000 |
| 1918 | 14 750 | 0·95 | 1 500 |
| 1920 | 18 750 | 0·8 | 1 500 |
| 1922 | 25 000 | 0·8 | 1 500 |
| Under construction | 47 500 | 0·8 | 1 800 |

About 1887, de Laval had developed a satisfactory form of double helical reduction gearing for use with his simple impulse turbine, and showed that single-reduction gears with a ratio of 10 to 1 could be successfully constructed for transmitting small powers.

About 1912, however, Sir Charles Parsons further developed this form of gearing for coupling to electrical machinery turbines of much greater output; and, by

---

[*] British Patent, Nos. 6 734/1884 and 14 723/1884.

[†] The term "high speeds" is used in a relative sense, i.e. in comparison with reciprocating-piston engine practice.

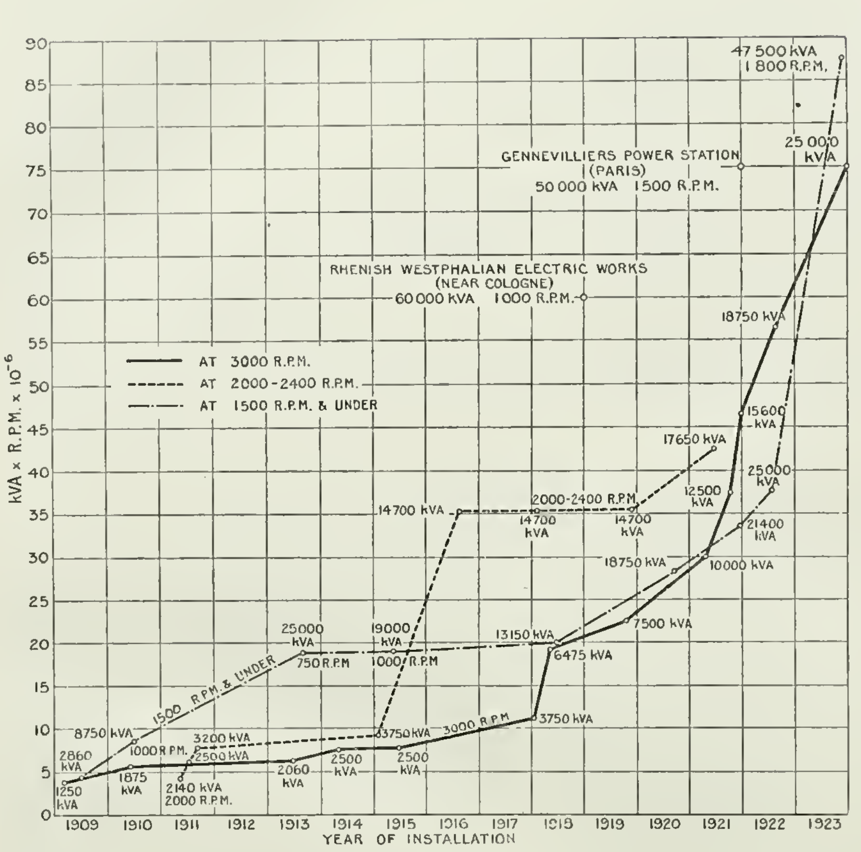


FIG. 1.—kVA × r.p.m. of the largest Parsons alternators manufactured each year.

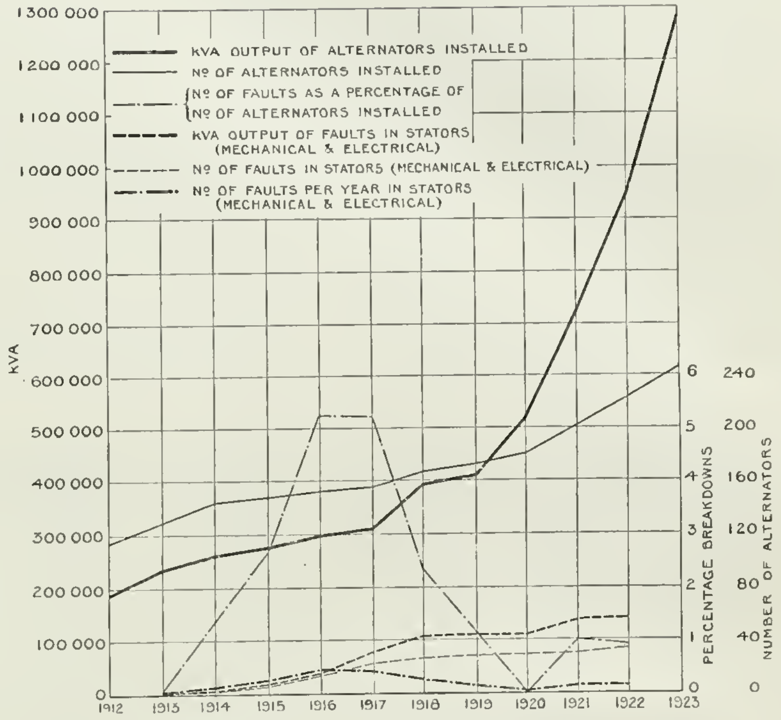


FIG. 2.—Output and number of Parsons turbo-alternators in commission.

FIG. 3.—Sand-blast action on conductors.

(This was shown as a lantern slide.)

the use of modern single-reduction gears, a turbine can be run up to some 5 000–6 000 r.p.m. : the speed of the alternator, now being optional, is made low (500–750 r.p.m.), so that ordinary materials and low-speed construction may be adopted, with a view to reduced cost.

With regard to large units, it is only within the last few years that alternators of very large output at high speeds of rotation have been built.

Table 1 gives the sizes of the largest Parsons alternators, of different speeds, manufactured each year, and demonstrates, on the whole, a gradual increase in capacity of individual machines. The curves in Fig. 1 perhaps illustrate this more clearly. During the period of the late war, the size of plant at 3 000 r.p.m. remained comparatively steady. The curves are of great interest, as it will be seen that the 14 700-kVA alternators, again referred to later in the paper, were a great advance upon machines running at the time. From the data obtained from the five 14 700-kVA alternators, experience was gained which enabled Messrs. Parsons to design and manufacture alternators of even greater outputs at 3 000 r.p.m., without exceeding the electrical and mechanical limits which had been proved satisfactory after several years' trial. Credit is also due to the Newcastle-upon-Tyne Electric Supply Company, and their consulting engineers, Messrs. Merz and McLellan, for their courage and initiative in installing a pioneer plant which was such a notable advance on any existing practice.

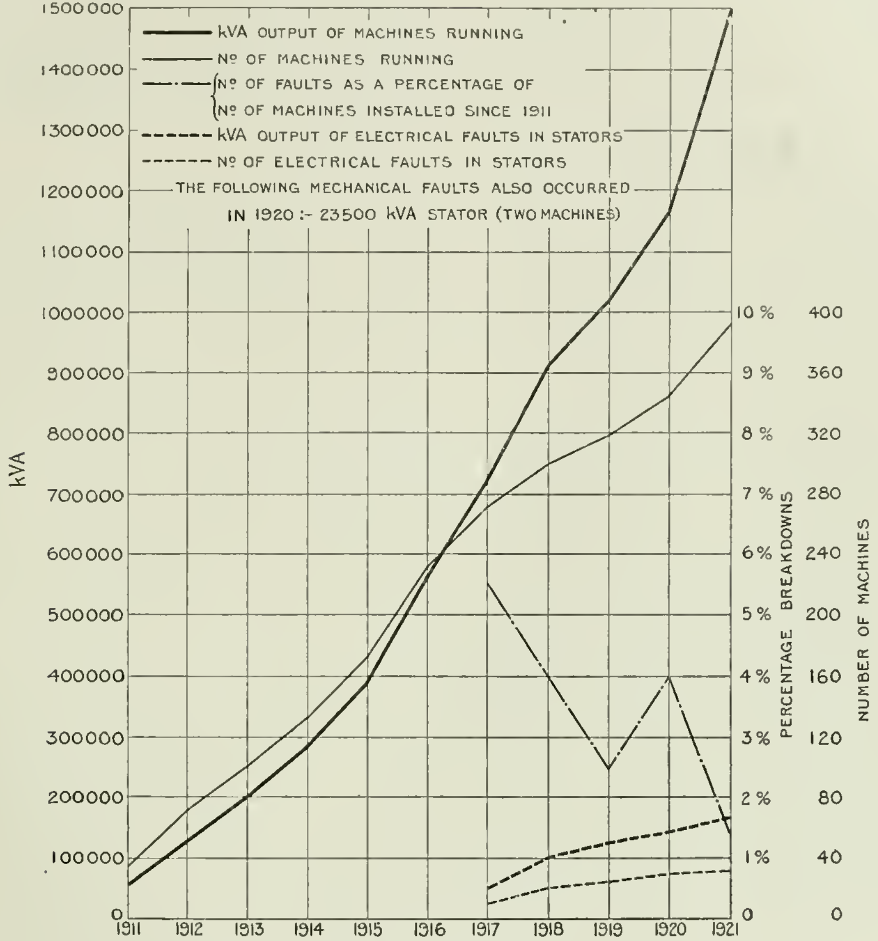


Fig. 4.—Number and output of Metropolitan-Vickers turbo-alternators in service.

In 1915, 3 750 kVA was considered to be a large output at 3 000 r.p.m., whereas, to-day, alternators of 20 000 kVA continuous maximum rating have been manufactured in this country. In America at present, 9 375 kVA continuous maximum rating is the largest output at 3 600 r.p.m. From the author's discussions with engineers and designers in America, he found that the difficulty in designing at the higher speeds lay in the alternator and not in the turbine, and that ventilation appeared to be a limiting factor.

With the improved materials and methods of ventilation, combined with more accurate proportioning, large alternators at high speeds are certainly no less reliable than the earlier and smaller machines. The accompanying curves, Fig. 2, indicate all the breakdowns of Parsons alternator stators in the British Isles during the past ten years. The total output and the number of machines installed during this period are also given.

During the period 1916–1917 there were several failures, due to reasons which are now clear, the faults being at the alternator terminals and on the end windings, due to overheating, insufficient supports against sudden short-circuits, and to station conditions such as moisture in air ducts. The two breakdowns for 1922 (Fig. 2) were of alternators built 20 years ago. One involved a minor repair, and the second machine had to be rewound. Only the failures of stators are included, as the failures of rotors of which the author has experience have been few during this period, and the difficulties have been mechanical and readily overcome. This record speaks for itself, especially when it is remembered that during a large portion of this period the plants were run at maximum output night and day, owing to war conditions. Although the number of machines in commission has increased, the number of breakdowns has diminished. The improvement is still more striking when it is considered that the conditions of operation in a modern power station have become more severe with the advance of time.

To achieve these results, advantage has been taken of every opportunity of incorporating later improvements into alternators already in operation. The results would have been even better had it not been that, because of the circumstances previously mentioned, it was not possible to shut down some of the plants even for a short time in order to make the necessary improvements.

In one plant some of the stator conductor insulating-tubes were found to be eroded. The ground near to the air-duct entrance to the alternator foundations was being excavated, and fine grit and dust were drawn into the alternator air-duct and air-gap, being thrown out by the rotor at a velocity corresponding approximately to its peripheral speed, causing a sand-blast action, which was sufficient to cut into the portions of the insulating tubes exposed between the core sections. The remainder of the tubes were protected by the core, as the slot was of the tunnel formation. A photograph of two of the conductor tubes is shown in Fig. 3. It is of interest to record that, although at least seven conductor bars were damaged, being bared to the copper, the alternator did not break down. Protection is now provided by means of teak-wood packing at the top of the slots, driven in along the whole length of the core.

The fault mentioned above was found during the annual overhaul, and emphasizes the advisability for periodic examination and testing in order to avoid mishaps which are beyond the control of both power station engineers and manufacturers.

Fig. 4 gives the curves for machines of the Metropolitan-Vickers Electrical Company's manufacture, which also show a downward tendency in the percentage of breakdowns.*

### (2) Mechanical Construction of Rotor.

The principal mechanical problems are encountered in the construction of the rotor. Improved methods of manufacture, and more systematic inspection and testing, have eliminated troubles due to flaws in the material.

The barrel formation of rotor, in which the exciting windings are embedded in radial slots formed between the poles, has proved itself eminently suitable for high-speed design. The details of the rotor construction depend upon experience, and upon the design of the remaining parts of the alternator.

When the first 14 700-kVA alternators running at 2 400 r.p.m. were under consideration in 1914, the problem of the best construction of rotor was thoroughly thrashed out. The merits of the plate rotor with a through shaft, of the plate rotor with bolted-on shaft ends, of the rotor built with thin laminations on a through shaft, and of the single-forging rotor, were given careful consideration by Sir Charles Parsons and the author. The simple solid forging was finally chosen, and experience has shown that it is the most suitable construction.

After careful consideration of the peripheral speeds of machines already running, it was decided to adopt the very conservative and safe figure of 300 ft. per second, at which peripheral speed several Parsons alternators had been running for many years at speeds from 1 000 to 3 000 r.p.m. Obviously this meant a long rotor body, and its length was actually 105 in., with a diameter of 29 in., giving a ratio of pole length to pole diameter of 3·62; this ratio was more than double that of any large alternator, either running or under construction, at that time. From careful calculations and comparison with these earlier machines it was decided that there might be a critical speed at 1 600 r.p.m. (On running the rotor of the first of these machines later, it was found to vibrate slightly between 1 200 r.p.m. and 1 600 r.p.m., but after the final balancing no undue vibration could be detected at or below 3 000 r.p.m., i.e. 25 per cent above the normal speed.)

It is of interest to note here that, in a paper read before this Institution in 1908, the pioneer Parsons direct-current armature was described,* having a core diameter of $2\frac{1}{4}$ in. and a core length of 8 in., giving a ratio of core length to core diameter of $3\frac{1}{2}$. This armature ran at 18 000 r.p.m. and had a through shaft. Most of the earlier rotors and armatures successfully ran through two or more critical speeds before reaching the running speed.

In addition to other novel features, the rotors of the 14 700-kVA alternators were water-cooled, and details are given in Section (5). It was realized that there might be difficulty in dissipating heat from such a long rotor by the usual methods of air ventilation, so that water-cooling was introduced to give confidence upon this question, leaving the designers a free hand to deal with the mechanical problems.

*Rotor caps.*—The caps for supporting the rotor end windings are one of the limiting factors in any design, and it is here that the advantages of comparatively low peripheral speeds become apparent. The material now obtainable for the caps has an ultimate strength of 65 tons per sq. in., with a yield point of not less than 48 tons per sq. in. The material is also ductile, as shown by the elongation on a test piece 0·564 in. diameter (area = 0·25 sq. in.), of 15 per cent on 2 in., with a reduction of area of 50 per cent.

---

* *Journal I.E.E.*, 1921, vol. 59, p. 299.

* *Journal I.E.E.*, 1908, vol. 41, p. 286.

With the comparatively low peripheral speed the stress in the caps is kept below 12 tons per sq. in. at the normal speed; in the 14 700-kVA alternators before mentioned the mean hoop stress in the caps was less than 9 tons per sq. in.

The rotor end windings are not evenly distributed under the caps, a circumstance that leads to a drawback, which is more apparent in the 2-pole rotors, namely that the caps, not being uniformly stressed, tend to become oval in service. Moreover, it is possible to deform a cap 25 in. diameter, 1 in. thick, by as much as $\frac{1}{8}$ in. on the diameter during its assembly over the windings. This phenomenon, when first observed, gave much food for thought, and it was considered desirable to obtain exact information as to the actual deformation of the caps with the completed rotor running at full speed. The investigations were carried out early last year (1921) and a rotor from a 15 000-kVA alternator running at 3 000 r.p.m. was selected for the experiments.

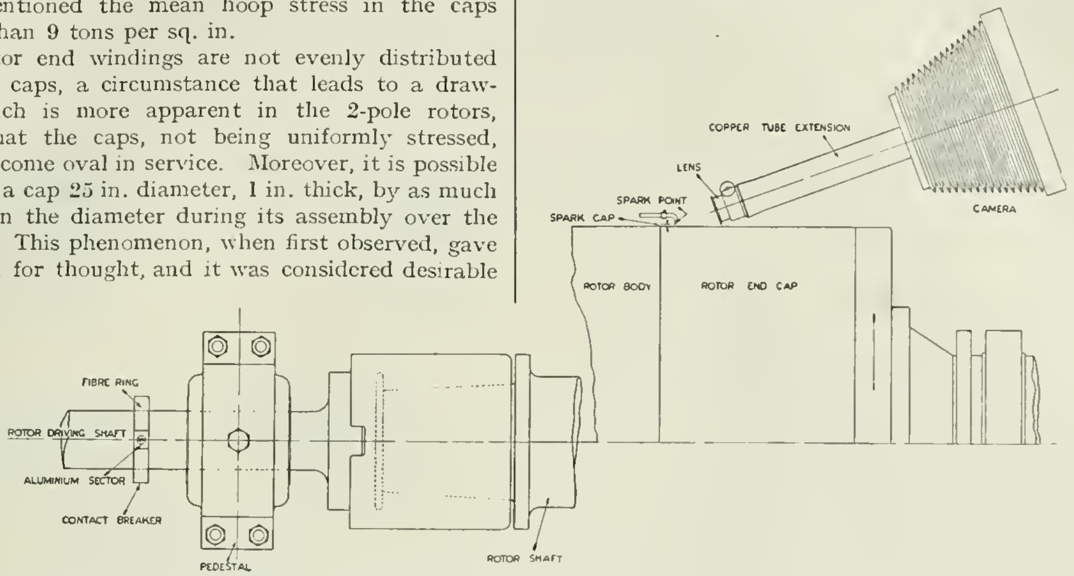


Fig. 5.—Experiment on rotor end cap, to determine the distortion when running at 3 000 r.p.m. Plan of apparatus for photographing spark.

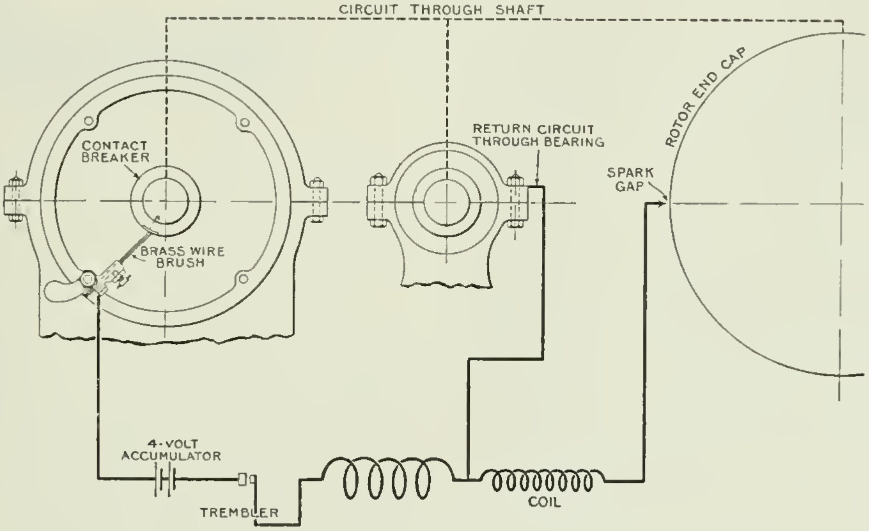


Fig. 6.—Diagram of connections for experiment on rotor end cap.

The rotor was adjusted in a special machine used for the dynamic balancing of alternator rotors, and was driven by a 600-b.h.p. low-speed motor, stepping up through a 6/1 gearing and flexible coupling, thus eliminating any side pull such as that due to a belt. The oil clearance between the rotor journals and bearings was a minimum.

The eccentricity of the cap was obtained by measuring the varying clearances between the cap and a fixed point or contact.

Two methods of obtaining the eccentricity were originally proposed:

(1) Using a microphone to record the loudness of the note in a telephone receiver, or to give a record on an oscillograph.

(2) Photographing the length of an electric spark jumping across the gap between a fixed contact and the cap.

The microphone method is inadmissible unless the cap is of magnetic material, and there is obvious difficulty in obtaining accurately, by this method, the shape of the cap while running; the second method was therefore adopted.

The maximum extension of the cap occurred adjacent to the rotor body. The extension on the diameter was 0·01 in. between poles, and 0·025 in. at the centre of the poles. The cap was therefore only slightly distorted. The results agreed very closely with calculation.

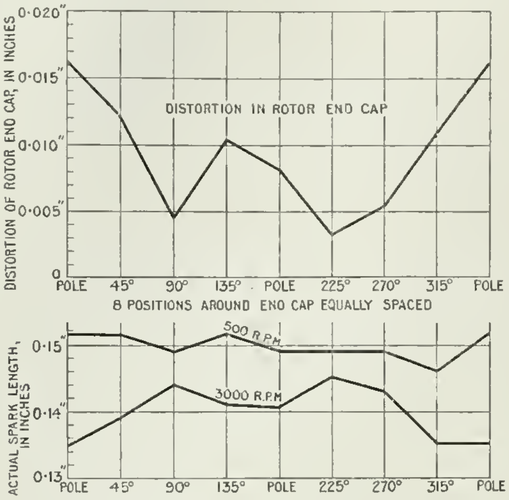


Fig. 7.—Graphs showing distortion in rotor end cap.

Table of Readings and Calculations from Experiment.

Spark Gap = 0·15 in.

| (1)<br>Position on rotor | (2)<br>Length of spark at 3 000 r.p.m. on film | (3)<br>Length of spark at 500 r.p.m. on film | (4)<br>Difference (3) − (2) | (5)<br>Actual distortion (4) × $\frac{0\cdot15}{1\cdot10}$ |
|---|---|---|---|---|
| pole | 0·99 | 1·11 | 0·12 | 0·0163 |
| 45° | 1·02 | 1·11 | 0·09 | 0·0122 |
| 90° | 1·055 | 1·09 | 0·035 | 0·00475 |
| 135° | 1·035 | 1·11 | 0·075 | 0·0104 |
| pole | 1·03 | 1·09 | 0·06 | 0·00815 |
| 225° | 1·065 | 1·09 | 0·025 | 0·0034 |
| 270° | 1·05 | 1·09 | 0·04 | 0·0054 |
| 315° | 0·99 | 1·07 | 0·08 | 0·0109 |
| pole | 0·99 | 1·11 | 0·12 | 0·0163 |

It will perhaps be of interest to give here a very short description of the experiment. The sparking contact, Figs. 5 and 6, was supported from the heavy baseplate and made adjustable axially along the cap. The brush of the contact breaker, which it was found more convenient to fit to the driving motor shaft, could be moved round to make the spark at any desired circumferential position on the cap. Fig. 7 gives in graphical and tabular form the results of one set of readings taken at 500 r.p.m. and 3 000 r.p.m. The procedure in calculation is given at the head of the table following Fig. 7.

At the former speed it was assumed that there was no appreciable distortion of the cap—the difference in the readings will therefore give the distortion due to the rotation at 3 000 r.p.m. The illustrations are diagrammatic, but some idea of the difficulties in running, and due to windage, may be gauged from them, when it is remembered that the maximum peripheral speed of the rotor, which weighed 15 tons, was nearly 400 ft. per second.

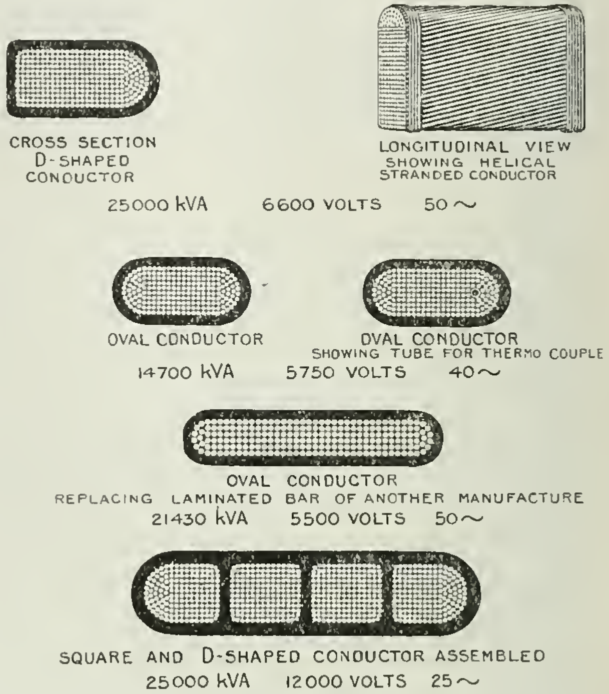


Fig. 8.—Sections of insulated conductors made from Parsons helically stranded coreless cable, without crushing.

Figs. 9 and 10.—Special cable-making machine.
(These were shown as lantern slides.)

### (3) Stator Windings and Insulation.

Early alternator stators were hand wound, with a continuous length of cable of the same cross-section throughout. The insulating tubes in the slots were moulded separately, usually of tape and fibrous material such as press-spahn or leatheroid. They were placed in position in the slots, and the cable was wound or pulled through them. The cable was insulated by hand during the process of winding. This construction, although of proved reliability, was laborious and expensive, and became more difficult with the increasing size of alternators. The winding space was not used effectively; the output was limited and the cost unduly high.

To overcome these difficulties, the conductors in the core are now made separate from the end connectors. The former are made by Messrs. C. A. Parsons & Co., of their stranded coreless cable,* shown in Fig. 8, in

* British Patent, Nos. 16 620/08 and 184 574.

which the individual strands are insulated and spiralled in a definite lay, to eliminate eddy-current losses in the cable. The end connectors are made of copper straps, which form a good mechanical construction for bracing against the forces set up in the winding at the moment of sudden short-circuits.

The cable employed is constructed on a special cable-making machine,* and is built up of copper strands separately insulated; it can be manufactured in any desired shape without a central core and without crushing. There is therefore no necessity to deform the cable after it leaves the cable-making machine. By this means the danger of short-circuits developing between individual strands is eliminated. Some examples are given in Figs. 9 and 10, illustrating the accurate forming of the cable, which leaves the machine in its final form without crushing.

There appears to be some misunderstanding in the minds of engineers as to the properties of the Parsons stranded cable. In the early days, when armatures were wound with round stranded cable, there was no difficulty in obtaining a good construction. However, later, with oval cables, cable makers would only supply round cable crushed to the desired shape, or a cable with a paper core. The former was undesirable, as the insulation on the individual strands of the conductor was broken in the process of crushing. As a result, excessive heating occurred due to the induced eddy currents. The paper-core cable had the obvious disadvantage of a low space factor, with the result that it was impossible to design an economical machine, and limits were placed on the output. This type of cable was also very difficult to handle and to bend into suitable shape for winding. The Parsons patented cable overcomes these difficulties, and to-day is gradually obtaining recognition, so that it is being used in the construction of transformers and alternators by other manufacturing firms in this country and on the Continent; in America its use is now under consideration. Later still, multiple joints * were adopted for connecting the cables forming the core conductors to the end connectors. This improvement is successful in minimizing the loss due to eddy currents induced in the joints. An example of a conductor with three separate joints at each end is given in Fig. 11.

With the improved winding construction, mica became, and still remains, the principal component in the material of the insulating tubes. Instead of the tube being formed and the conductors wound separately, the slot insulation is moulded round the conductors, forming one bar ready for placing into the slot. The insulation is applied by the Parsons Company by a special machine, the design of which is based on the principle of the familiar hand cigarette-making machine. The insulation passes over a hot table and is carried round by a taut canvas band, being thus tightly wrapped round the stator conductor bar. The machine in question is sufficiently flexible to be able to insulate a small bar weighing a few pounds, up to bars weighing 3 cwts. The end connectors are also insulated separately before assembly in the stator; after assembly, it is only necessary to insulate the joints connecting the end windings with the slot conductors. With these new methods employed in winding, it has become possible to use improved insulating materials, and to supervise more strictly this important part of the work.

In earlier practice, methods of manufacture had been developed in which the insulation moulded round the conductors formed a compact mass with the copper, and had almost a metallic ring when knocked with a hammer; conductors insulated in this way made a great appeal to engineers, owing to their resemblance to a

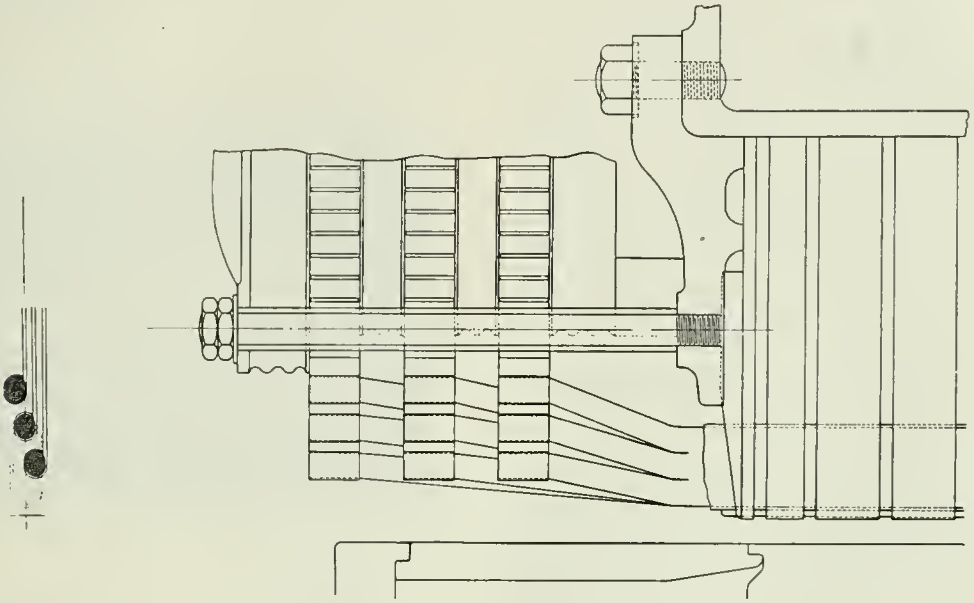


Fig. 11.—Multiple joints for stator end connections.

---

* British Patent, No. 16 620/08.

* British Patent, No. 126 124.

metallic structure. The disadvantages of this method of insulation did not appear until later.

During 1913, on drying out the stator windings of a 2 500-kVA, 6 600-volt alternator, cracks developed in the hard insulating tubes, which broke down to earth under the high-pressure insulation test. The reason for this failure was not appreciated until a similar fault developed on another stator, and the whole position was investigated. The explanation is a simple one. When the alternator gets hot, the conductors and insulating tubes expand and lengthen. The copper conductor, having the higher coefficient of expansion, lengthens more than the tube and, as both form a solid mass, one has to give way. It is always the tube. This illustration shows clearly how a modification, although apparently an improvement, may have disadvantages which only develop on trial under operating conditions. It shows also the necessity for caution in departing from proved methods of construction.

Yet, on looking into other spheres of electrical work, it is not unreasonable to reflect that the difficulties might have been foreseen. Take one example—an ordinary electric glow lamp. The metal "leads" to the filament must have the same coefficient of expansion as that of the glass through which they pass, otherwise, when the lamp is switched on, and becomes heated, the glass and wires expand unequally and the glass cracks.

To remove the expansion difficulty, and to retain the insulating tube moulded directly on to the conductors, it is necessary to use an insulation having the same coefficient of expansion as that of copper, or, alternatively, to make the insulation sufficiently flexible to take up the difference in expansion. The former solution is not yet obtainable. A flexible mica insulation had therefore to be devised. This insulation, after a great deal of investigation, was finally obtained and, when the spirit has been evaporated from the varnish binding the mica flakes together, the remaining oils ensure that the insulation retains sufficiently elastic properties at the operating temperatures of the alternator. It must be remembered that the sides of the conductor slots also grip the insulating tube; just as between the copper conductor and the tube there is relative movement, so is there also between the tube and the iron core. Flexible insulation has provided a satisfactory solution of both difficulties.

As an alternative, if a hard moulded insulation is used, the following precautions should be taken. A thin layer of flexible insulation should be applied between the conductor and the hard tube, and also outside the latter. This outer layer of elastic material might be applied to the sides of the slots so as to present a smooth surface to the insulating tube. A suitable bituminous compound, becoming elastic at the operating temperatures, would serve the purpose.

It must be borne in mind that whatever insulation is employed must not be brittle. If brittle insulation is used, cracks will also develop when the windings are subject to the forces occurring on short-circuits. The insulation must not pulverize. Too much stress cannot be laid upon these qualities.

Experience has proved that movement of the end windings as a whole cannot entirely be prevented. On one occasion a dead short-circuit occurred across the terminals of one of the largest alternators while on full load. Careful examination showed that, owing to the shrinkage of insulation and packings relieving the pressure of the clamps, the stator end windings in one place had moved $\frac{1}{2}$ in., but had afterwards sprung back to their normal position.

### (4) Stator Slots.

In the author's opinion, the tunnel formation of slot for receiving the stator conductor bars has many advantages over the open slot formation. The construction may be a little more expensive to manufacture, but, when correctly designed, the windings are more accessible for examination and withdrawal, if necessary, than former-wound coils in completely open slots. This advantage is more noticeable in turbo-alternators, as the number of poles rarely exceeds two or four, giving a long winding-pitch. The advantages are also still more apparent in the largest turbo-alternators, since the number of conductors per slot is small.

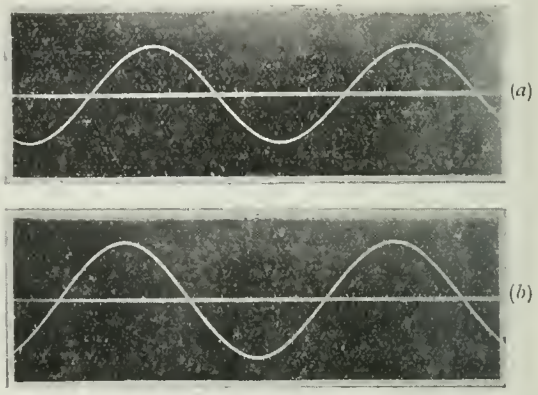


Fig. 12.—Oscillograph curves for 18 750-kVA 6 500-V alternator on open circuit.

(a) Between phases. (b) Between phase and earth.

The slot is punched with a full radius top and bottom, giving a sound mechanical construction of core, and the insulating tube, of the oval cross-section required to fill the slot, is readily moulded around the conductor bar.

With the tunnel slot construction the flux pulsations are minimized, and, as the stator bore has an uninterrupted contour, the circulating currents induced in the rotor body are reduced to a minimum and the efficiency of the alternator is improved. In the closed slot construction the leakage of flux across the iron bridge enables a high inherent reactance to be obtained without resorting to abnormal proportions of the slot.

Again, by the use of the tunnel slot it is possible to obtain an alternator voltage wave-form entirely free from ripples. With the open type of slot it is difficult to remove the ripple at the peak of the voltage waveform. Fig. 12 gives the oscillograms of the open-circuit voltage of a Parsons 18 750-kVA alternator with tunnel slots. Fig. 13 gives the oscillograms with a load of 8 000 kVA and a power factor of 0·95. Both sets of oscillograms give the voltage between phase terminals, and between the phase terminal and the star point. There are no pronounced harmonics, and on load the maximum deviation from a sine wave of the pressure between the line terminal and earth is 2·1 per cent. This improvement in wave-form is most desirable, especially where the supply of power is given through transformers or through converting apparatus such as rotary converters. It avoids disturbance in telephone operation and difficulties with parallel running, since it eliminates circulating currents, and it gives the supply engineer opportunities to earth without anticipating trouble.

If tooth ripples are present in the voltage wave-form, there is the danger of resonance in the distribution system causing breakdowns of the cable insulation. Such a series of failures was recently brought to the author's notice; they were finally ascribed to the above cause, and were overcome by connecting in circuit another feeder to alter the impedance of the external circuit.

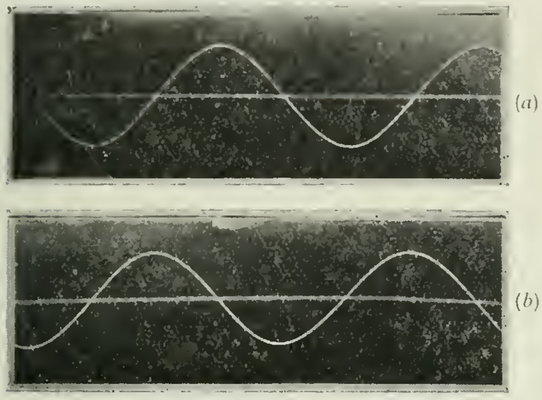


Fig. 13.—Oscillograph curves for 18 750-kVA 6 500-V alternator on load of 8 000 kVA at 0·95 power factor.
(a) Between phases. (b) Between phase and earth.

Fig. 14.—Stator tooth supports of different dates.

Fig. 15.—The effect of the vibration of spacers and core plates in a particular case.

(Figs. 14 and 15 were shown as lantern slides.)

Some years ago, two power stations about one mile apart were running in parallel, and it was found that the electrical instruments in one station were indicating more load than the alternators could possibly give, whereas the recorded output at the second station was too low. This error in the reading of the instrument was finally traced to the high-frequency circulating currents through the alternator star-points, which were earthed in both stations.

*Stator tooth supports.*—The supports to the teeth between the slots have in the past been a source of difficulty. Views of the supports used at different dates are given in Fig. 14. The **H**-section spacer shown at A has proved to be the most suitable support. The **U**-shaped spacer shown at B gave trouble due to insufficient bearing surface. In one alternator the vibration of the spacers and core plates was sufficient to taper away the spacer to less than half its original height, and to cut through the adjacent thick plates supporting the core, as illustrated in Fig. 15. Some of the spacers broke away at the shoulder and were pulled on to the periphery of the rotor. At the time the fault was found, it was impossible to shut the machine down and provide a remedy, as there was no other plant available to take the load.

### (5) Ventilation.

With the larger sizes and longer lengths of alternators (necessitated by comparatively low peripheral speeds) it becomes more difficult to ensure uniform cooling. In the usually accepted schemes of ventilation, air is drawn or forced in from the ends of the alternator only. The available area for the passage of air is limited, and the air is heated before getting to the centre of the alternator, which is consequently the hottest part. Such local high temperatures limit the output.

To obtain a scheme of ventilation in which the alternator shall be cooled uniformly throughout its entire length should be the aim of all designers, and it is necessary that the construction should be simple and easy to manufacture. Such a method is described in British Patent No. 15 585/1914, and, so far as the author is aware, the practical application of this scheme of ventilation is unique. The alternator, for ventilation purposes, is divided into separate air circuits in parallel, each with low resistance to the passage of the air. By this subdivision the alternator can be designed to have any desired length, and still be uniformly cooled. Fans attached to the rotor, or separately-driven fans, can be used. From Fig. 16 it will be seen that the air is forced into the separate pressure belts or compartments A, which are cast into the stator casing, alternating with the exhaust compartments B throughout the length of the alternator. From each pressure compartment the air passes through radial ducts into the body of the core. A portion of the air then passes between the stator teeth K round the conductors into the air-gap, where it divides and passes axially in both directions, and back radially into the adjacent compartments B. Only a portion of the air passes between the stator teeth K, the remainder being short-circuited through axial holes M, formed in the core immediately behind the conductor slots; this air joins the stream passing from the air-gap back into the exhaust compartments. The quantities of air short-circuited behind the conductors and passing through the air-gap are so proportioned as to obtain uniform cooling of all parts of the stator and rotor.

The stator end windings are ventilated from the end pressure compartments A1, from which the air is forced through suitably designed holes C in the end walls of the casing on to the end windings. Baffles are provided to direct the air round these windings before leaving at the outlet D in the end-winding protective shields P. These baffles (Fig. 17) are so designed and arranged that the cool air impinges on each section of the end windings, eliminating hot spots.

The rotor is mainly surface cooled, but, in addition, air is also drawn in under the balancing discs E. A portion of this air is forced through the holes F in the rotor end caps, and the remainder is drawn into the axial slots G machined along the rotor poles. Gaps H are left between the keys in these ventilating slots, so that air is thrown out opposite the exhaust compartments in the stator casing.

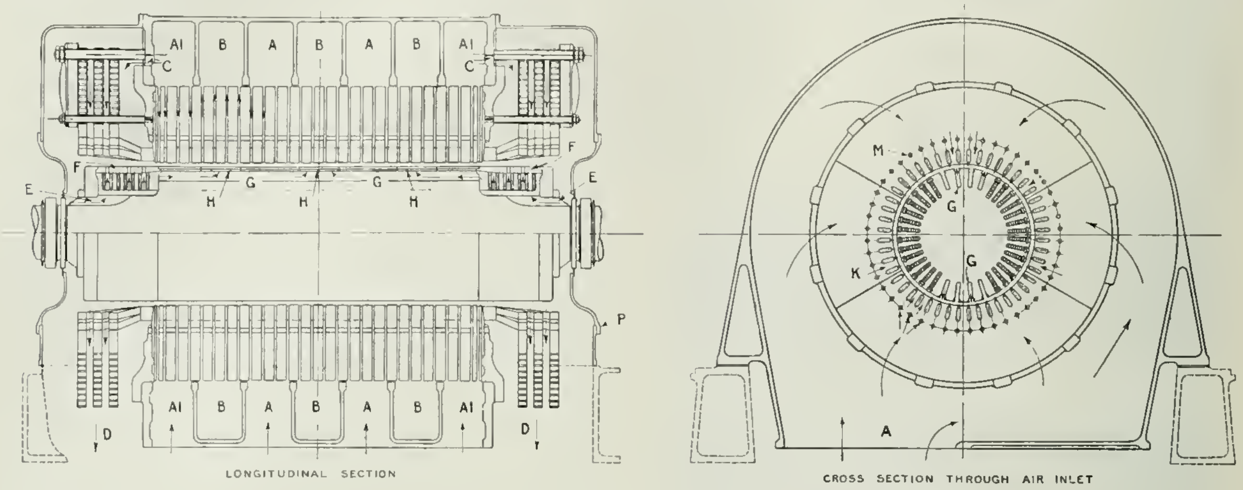


FIG. 16.—Parsons ventilation system of an alternator.

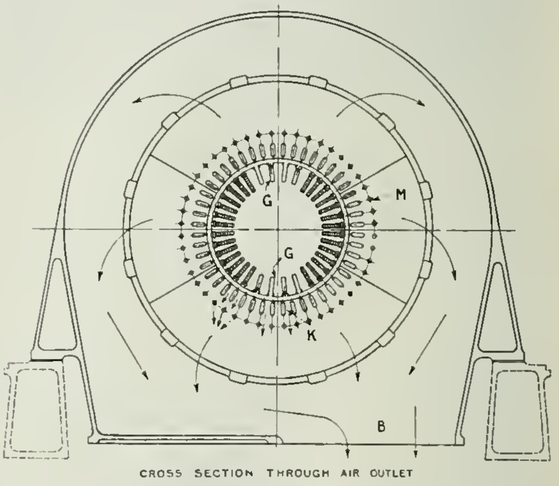


FIG. 17.—Design and arrangement of air baffles.

(This was shown as a lantern slide.)

With the scheme of ventilation described, a separately-driven fan is recommended. It is impracticable to construct a highly efficient fan for fitting on the ends of the alternator rotor. When integral fans are used, sufficient air is passed only at the expense of unnecessary power and consequent loss of efficiency. It is also impracticable, without increasing the length of the plant unduly, to obtain a suitably designed vortex chamber in the end shields, owing to the restricted space available and to the baffling effect of the stator end windings. The author has had considerable experience of separate motor-driven fans on alternators of all sizes, and on none of these plants has a breakdown occurred on either fan or motor. It is needless to point out that it is essential to obtain a good design of fan and motor, and to see that the latter runs well within its maximum rating. The motor-driven fan can be designed with the maximum efficiency, and it has been proved that a consequent gain of as much as 1 per cent in the efficiency of the alternator is possible.

*Air cleaning.*—A large quantity of air is used to cool an alternator, and its weight may actually exceed that of the steam passing through the turbine per unit time; it is therefore essential that the air should be clean. A 10 000-kW turbine, with a steam consumption of 10·0 lb. per kilowatt-hour, passes 1 670 lb. of steam per minute, whereas the weight of the ventilating air passing through the alternator is 2 740 lb., i.e. 45 per cent more during the same period, assuming a flow of 36 000 cubic ft. per minute.

Until comparatively recently, it was the universal practice to ventilate the alternator by means of a continuous stream of fresh air forced through it, either by separately-driven fans or by fans integral with the alternator rotor. In this system the heated air may be either thrown away outside the engine room, or utilized in the boiler stokeholds for the combustion of the fuel. If efficient means of cleaning the air were not adopted, the passage of the very large quantities of fresh air necessary would quickly result in the silting up with dust of the ventilating ducts through the alternator windings and core.

In the early days the cleaning apparatus consisted of filter cloths, presenting a considerable surface to the passage of the air. The principal disadvantages of this apparatus are :—

(1) The large space occupied.
(2) The necessity for periodic removal of accumulated dust, some of which reaches the windings in spite of all precautions.
(3) The danger of fire, due to the inflammable nature of the filter cloth.
(4) The length of external ducts for conveying the air.

As a result of the first three disadvantages mentioned, the dry air-filter was generally superseded by the wet air-filter, in which the air was brought into intimate contact with water.

In this type of filter it is possible not only to clean the air, but also to lower the temperature of the air entering the machine below that of the surrounding atmosphere. The great disadvantage of the wet air-filter is that there is always a danger of free moisture being carried over into the alternator and collecting on the windings. This danger cannot be altogether eliminated even with long air ducts, large settling chambers, and fans between the filter and the alternator.

In 1913, few reliable data were available as to the conditions under which wet air-filters were operating. Messrs. C. A. Parsons and Co. decided to investigate thoroughly the whole position, and tests were carried out on a number of filters of various makes installed in different parts of the country. These tests showed that in a great many plants free moisture was present in the filtered air entering the alternator. In some machines the insulation resistance of the stator windings was reduced to a dangerous figure. The fault was not only in the filter, but also in the lay-out of the ducts between the filter and the alternator. The circulation of air through the filter was not uniform. As the danger due to free moisture was so great, a number of wet air-filters were put out of commission, and in other plants the water was periodically shut off from the filters so as to give the alternator insulation resistance time to rise.

A wet air-filter of a capacity of 25 000 cubic ft. of air per minute was installed at the Heaton works, and exhaustive tests were made on it. The results clearly indicated that the design of filter under test was wrong. A new type of wet air-filter resulted. Although more reliable wet air-filters are now available, great care must be taken in the lay-out of the filters in relation to the alternator, and precautions must be taken in their operation. The filters are sometimes put out of commission during frosty weather owing to the danger of the water freezing. Steam heaters have been used to overcome this difficulty.

It was felt, however, by Messrs. Parsons that the time had come to attempt to eliminate the difficulties due to the air coming into contact with water. It was suggested that some form of apparatus which cooled the air circulating round a closed system of ducts might be an improvement; the same air would be repeatedly circulated, and it would therefore not be necessary to clean, but only to cool it. In addition, it was decided that the air must not come into contact with the cooling fluid. Some years previously this same question had been discussed, but at that time it was considered inadvisable to proceed with such a cooler which, with the data then available, was found to be both cumbersome and expensive to manufacture.

Renewed tests were now started on a design of air cooler which was in fact a motor-car radiator in reverse operation, its function being to absorb heat from the air instead of to dissipate it. The cooler under test had copper tubes with sheet-iron gills, and was in reality a radiator taken from a 4-ton lorry. As a result of only a few experiments, it was found that such an air cooler was a commercial proposition. Elaborate experiments were carried out with an enclosed system of ducts, with the same air repeatedly circulated. An electric heater was used in the ducts for heating the air, the heat being subsequently extracted by the cooler.

Credit should be given to the staff of the Battersea Corporation Electricity Works who, in 1912, took out a patent for a cooler using water from the condensate, and proved the advantages of the enclosed air system. They installed their first cooler at Battersea power station, using plain tubes. The whole question was discussed with Messrs. Merz and McLellan, and an alternator air-cooler, to deal with 18 000 cubic ft. of air per minute, was installed in 1919 by Messrs. Parsons, on a 3 000-kW plant in the Blaydon power station of the Newcastle-upon-Tyne Electric Supply Co., to whom credit should also be given for placing an order for experimental plant for commercial use. This alternator air-cooler which, since its installation, has run without any fault developing, was the first design with gilled tubes to be installed and put into commercial operation in this country. The Parsons Company has a number of coolers for alternators, with a total capacity of a quarter of a million kVA, either in operation or under construction, for this country or abroad. At the time the above-mentioned cooler was installed, the General Electric Co. of America was apparently experimenting on the same lines, and some of their results were published.*

There are several advantages attached to the closed-circuit system of ventilation. It is generally possible for the cooler to be installed inside the alternator foundation block, the only external plant being the fan with its short connecting air ducts. The system is therefore very compact. Little or no dirt can collect in the alternator, since practically the same air is continuously circulated round the system. Owing to slight unavoidable air leakages (which have to be made up) it is true that the circulated air is very gradually replaced, but the ducts can be so arranged that the leakage occurs at one point only, the incoming air being previously cleaned and dried. In the author's experience, however, this complication has proved unnecessary.

Another advantage of the closed-circuit system lies in the fact that it reduces the fire risk, as the actual weight of air available to feed an internal fire in the machine is small and the oxygen therein would be rapidly consumed. The weight of air in the system of a 10 000-kW alternator would be only 80 lb.

---

* *General Electric Review*, 1920, vol. 23, p. 99.

The designers of the Gennevilliers power station, Paris, where coolers are installed, have planned a system for increasing the nitrogen content in the air to such an extent that it will not support combustion. This, in the author's opinion, is an unnecessary procedure.

Fig. 18 illustrates a simple lay-out of the closed-circuit air system of ventilation. The air is forced from the outlet of the fan D, through the alternator, into the foundation block in which is embedied the cooler C. On leaving the cooler, an air conduit E leads the cool air back to the suction side of the fan D.

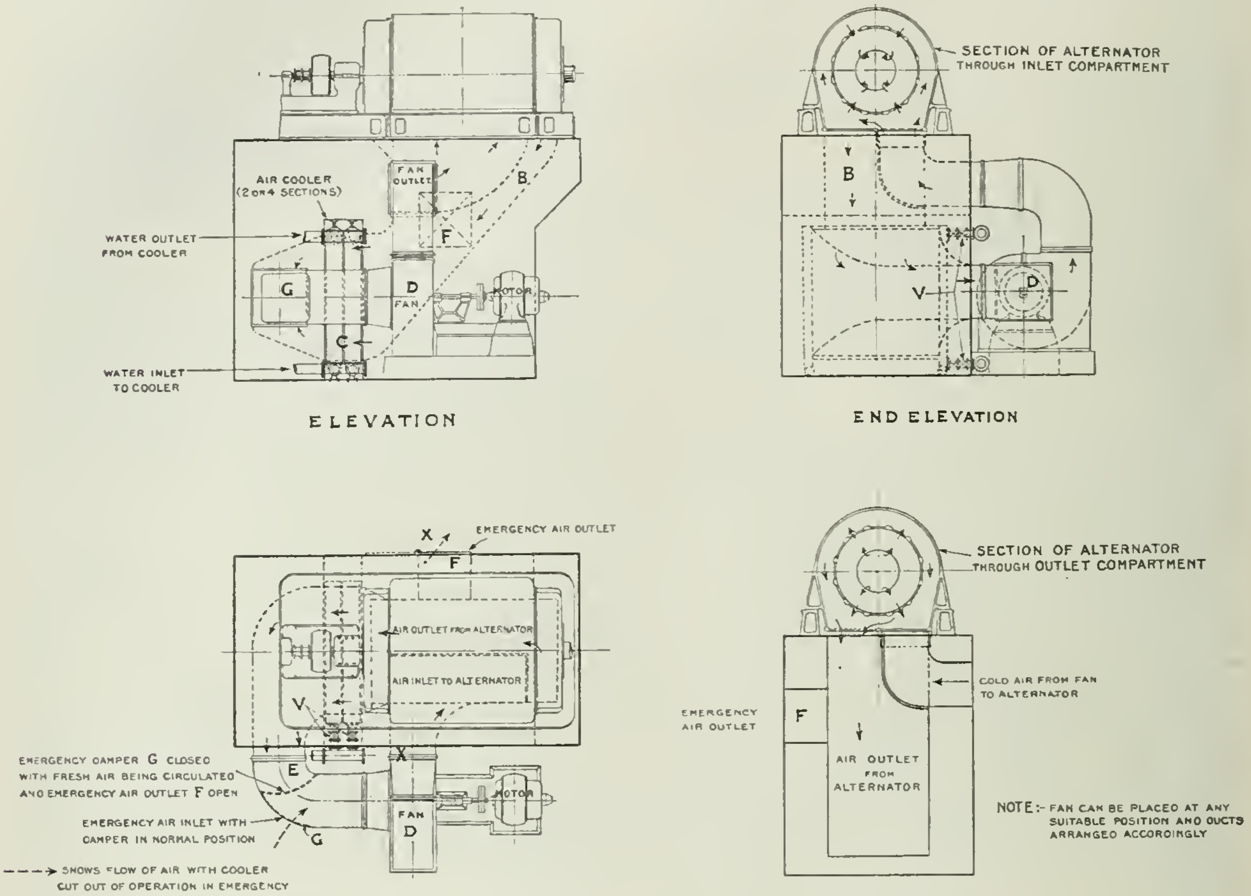

AIR COOLER
(2 OR 4 SECTIONS)
FAN OUTLET
B
F
WATER OUTLET FROM COOLER
G
D
FAN
MOTOR
C
WATER INLET TO COOLER
ELEVATION
SECTION OF ALTERNATOR THROUGH INLET COMPARTMENT
B
V
D
END ELEVATION
X
EMERGENCY AIR OUTLET
F
AIR OUTLET FROM ALTERNATOR
AIR INLET TO ALTERNATOR
V
X
EMERGENCY DAMPER G CLOSED WITH FRESH AIR BEING CIRCULATED AND EMERGENCY AIR OUTLET F OPEN
E
EMERGENCY AIR INLET WITH DAMPER IN NORMAL POSITION
G
FAN
D
MOTOR
SHOWS FLOW OF AIR WITH COOLER CUT OUT OF OPERATION IN EMERGENCY
PLAN
SECTION OF ALTERNATOR THROUGH OUTLET COMPARTMENT
COLD AIR FROM FAN TO ALTERNATOR
EMERGENCY AIR OUTLET
F
AIR OUTLET FROM ALTERNATOR
NOTE:- FAN CAN BE PLACED AT ANY SUITABLE POSITION AND DUCTS ARRANGED ACCORDINGLY
SECTION THROUGH X.X.

Fig. 18.

Usually the cast-iron water boxes of the air cooler are placed vertically, so that the water tubes are horizontal, the passage of the water being two-flow. By the provision of special ferrules on the water tubes of the coolers, single tubes can be readily withdrawn for inspection and replacement.

The coolers are built in two or more sections, each section being mounted on wheels or rollers and arranged to fit into guides in the floor and ceiling of the air-cooler chamber. Valves V (Fig. 18) in the water service enable a section to be isolated, and facilitate the withdrawal of individual sections. The handling of the latter, after being withdrawn, is effected by the means ordinarily available in the power station. Doors F and G (Fig. 18) are provided in the foundation air conduits to give access for inspection purposes, and to enable external air to be passed through the alternator when required. In the latter event, door G would be swung round so as to prevent further circulation of air through the cooler via the alternator when the latter is out of commission.

The water-box covers can be removed for cleaning the tubes without removing the cooler sections. The arrangement of the coolers in two or more sections enables any one section to be opened for cleaning, or to be removed for overhaul, while the alternator is in commission; the plant is operated meanwhile with the remaining sections, with somewhat increased air temperatures.

To prevent the possibility of the circulating water entering the air passages of the cooler, it is desirable that, wherever possible, the water tubes of the cooler should be arranged on the suction side of the circulating water pump, so that the water pressure in them would be less than that of the circulating air, which would be drawn into a puncture or leaky joint, instead of the water being ejected into the air. The cooler can be tested periodically for possible leakages when the alternator is out of commission.

A knowledge of the quantity and temperature-rise of the water passing through the cooler affords a ready and accurate method of checking the heat losses of the alternator and fan.

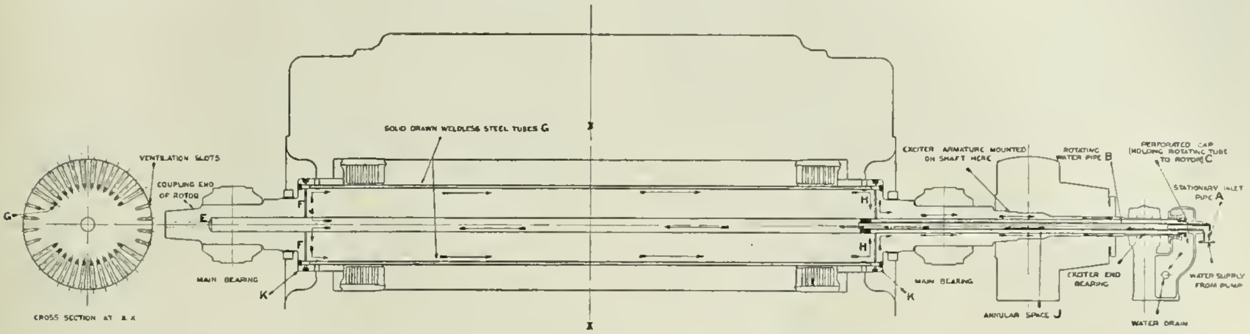


FIG. 19.—Longitudinal section through water-cooled rotor.

*Water cooling.*—The use of a liquid cooling agent has always appealed to the designer of dynamo-electric plant. It was first applied to electrical machinery by Sir Charles Parsons in his original very high-speed dynamos, built during the period 1884 to 1889. The armature shafts of these dynamos were hollow, and cool oil was continuously pumped through to the outboard bearing. The innovation was subsequently discarded as relatively ineffective.

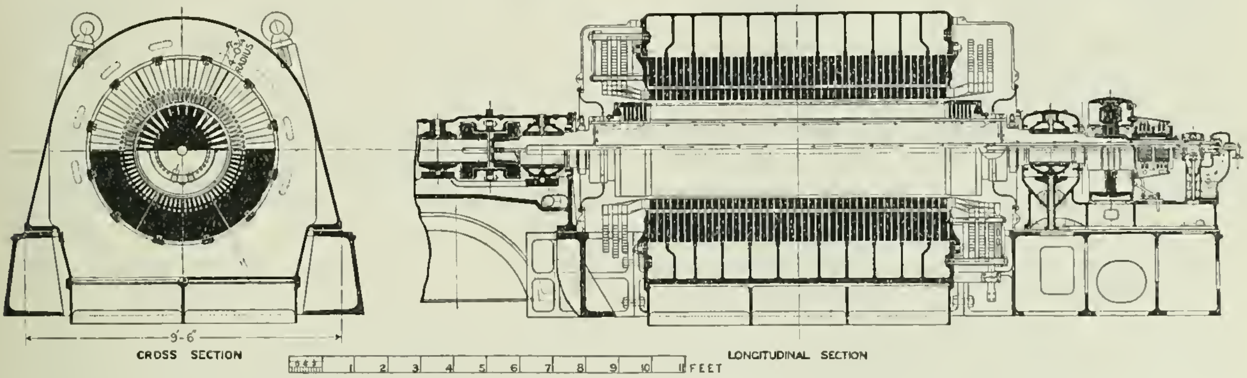


FIG. 20.—18 000-kVA, 5 750-V, 40-period, 2 400-r.p.m. three-phase alternator, 0·85 power factor.

In 1904 or 1905, an alternator was built in which, as an experiment, water pipes were fitted in the radial ducts of the stator core, the dimensions of the ducts being similar to those of the customary air passages. Later, in 1905, the stator core of another alternator was cooled by a group of longitudinal water pipes, which passed through specially provided tunnels and were connected to water boxes forming the supports for the ends of the core. The most modern scheme * of water cooling used at present is illustrated in Fig. 19; the rotor is cooled by water which enters and leaves at the same end, giving uniform cooling throughout and avoiding the complication of having water connections at the coupling end of the rotor.

Thus, in Fig. 19, the water enters through the small stationary inlet pipe A, into the rotating tube B fixed to the rotor shaft. It passes along the central axis of the rotor radially outwards through the holes F, and returns through the longitudinal weldless steel tubes G placed immediately under the rotor windings, and so radially inwards, through the radial holes H, to the annular space J between the pipe B and the rotor body, exhausting through the perforated cap C into the water box formed in the end pedestal. The whole design is simple and free from danger.

The joints to the pipes G are made externally to the stator end shields, so that any leakage developing would be immediately apparent, and not dangerous to the alternator stator. The tubes are expanded into holes in the collars K machined from the rotor shaft, and the holes plugged. Any leakage along the tubes from the joints is thrown off by centrifugal force, and there is no danger of water coming into contact with either the stator or rotor windings.

The same water is repeatedly circulated through the rotor and is cooled in a separate surface cooler. The cooling water is normally supplied from the condenser circulating water system. The closed water system for the rotor is adopted, since it is found necessary to add chemicals to the water in order to prevent corrosion of the water passages. Fig. 20 gives two views of an 18 000-kVA alternator with a water-cooled rotor, and it will be of interest to give a few details of this machine.

---

* British Patent, No. 16 986/1914.

The output is 18 000 kVA, three-phase, 5 500–6 000 volts, 40 periods, at 2 400 r.p.m. The stator core has an internal diameter of 35 in., and a length of $108\frac{1}{4}$ in. There are 72 slots, or 12 slots per pole per phase, and each slot contains one conductor, so that there are 24 conductors per phase. The stator flux $\phi = 156\ 500\ 000$ magnetic lines per pole, and the effective pole-arc being 29 in. (or 53 per cent of the pole-pitch) the mean density at the armature face is 50 200 lines per square inch. The peripheral speed of the rotor is 345 ft. per second, so that the centrifugal force of the material at the periphery is 2 700 times the force of gravity.

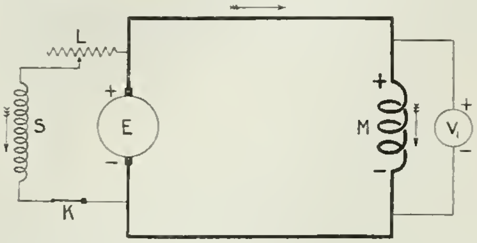


Fig. 21.—Shunt-wound exciter. Normal condition.

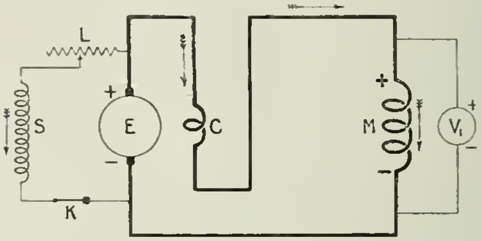


Fig. 23.—Compound-wound exciter. Normal condition.

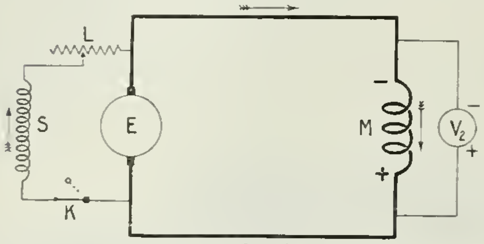


Fig. 22.—Shunt-wound exciter. Main field acting as a generator; exciter field and polarity reversed.

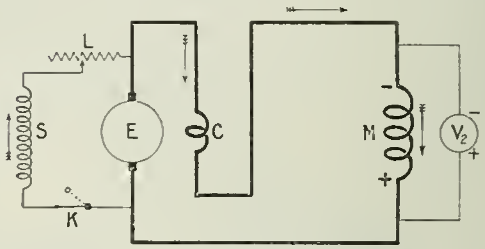


Fig. 24.—Compound-wound exciter. Momentary condition showing current in series winding overcoming effect of reversed shunt field current, main field acting as generator, and exciter terminal polarity reversed.

Figs. 21, 22, 23, 24.—Stability of exciters.

E = Exciter.
S = Exciter shunt field.
$V_1$ = Normal exciter voltage.
L = Shunt field rheostat.
K = Shunt field switch.
$V_2$ = Several times normal exciter voltage on sudden short-circuit.
C = Exciter series winding.
M = Rotor winding.

The output coefficient $d^2l$(r.p.m.)/kVA of 17 700 is lower than is usual for this size of plant. The increase in output for a given carcase, however, does not as a rule warrant the additional expenditure entailed in the manufacture of a water-cooled rotor. Only in special circumstances can water cooling be efficiently employed, e.g. in rotors where cooling water considerably below atmospheric temperatures is available. In using cold water, every precaution must be taken to avoid surface condensation of moisture from the air.

By the use of water it was possible to obtain a very useful indication of the losses occurring in the rotor body, including excitation losses and eddy-current losses under various load conditions. The actual power absorbed in the 18 000-kVA design at full output was 35 kW, the excitation loss being only 42 kW.

At the time the water cooling of rotors was adopted, it served a very useful purpose in providing an additional safeguard in the design of plant very much more advanced than any preceding it.

### (6) Instability of Exciters.

Difficulties have been encountered the world over with the instability of exciters. This instability shows itself in two ways:

(1) The exciter voltage tends to creep when the alternator is running at no load, and it is difficult to steady the alternator voltage for synchronizing. This is due to the absence of saturation in the exciter magnetic circuit at the low exciting voltage.

(2) Reversal of the exciter shunt-field current and exciter polarity. If this occurs when the alternator is running in parallel with other machines, the rotor drops back a pole-pitch and continues to give its load.

As a rule the effects of instability can be overcome by the provision of a main field regulator, which enables the exciter to work well up on the saturation curve. The introduction of the main field regulator is, however, not essential, as the regulation of an alternator can be readily carried out by means of a well-designed exciter field rheostat, with an exciter designed suitably for the lower voltages required for synchronizing the alternator. The use of a main field regulator also involves carrying the leads away from the alternator and introduces apparatus which is costly, and may give trouble and cause interruptions of supply. If no main field regulator is used, the main exciter leads can be carried straight from the exciter to the slip-rings and a main field ammeter of the shunt type used. It is advantageous, therefore, to eliminate the main field regulator and to design the exciter to be stable over a very wide range of voltage.

The first-mentioned difficulty, evidenced by the creepage of voltage, has been overcome by introducing saturation gaps in the exciter magnetic circuit, by suitable designs of magnet frame and, in slotted armatures, by working the armature teeth at a high magnetic density.

So far as the author is aware, the phenomenon of the reversals of the alternator excitation current has not hitherto been explained, so that the following explanation may prove of interest.

In Fig. 21, E is the exciter coupled to the main field winding M, its shunt field being indicated by the letter S. It will be clear that if the shunt-field switch K is opened suddenly, the voltage generated by the exciter at E will rapidly collapse, but since this voltage is applied across the magnet winding M, which has a high self-induction, the current in the circuit EM does not fall so quickly. Consequently, the back electromotive force of the magnet M continues to supply the circuit EM after the field circuit S is broken, and the exciter voltage has dropped away, but, referring to Fig. 22, it will be seen that the polarity at the exciter terminals is actually reversed. With the exciter brushes set in the usual position in advance of the neutral, the exciter armature current has a demagnetizing effect on the exciter field and causes reversal of polarity; but if the brushes were rocked to a position behind the neutral, the current through E would have a magnetizing effect and would tend to preserve the original polarity of the field. Thus this type of instability could be remedied by rocking the brushes backward. The same remedy could be equally well applied by putting compounding turns on the exciter field. These turns must be directly compounding, and not demagnetizing turns. The reason for this is apparent, as when the field circuit S is broken (see Figs. 23 and 24), although the polarity at the exciter terminals is reversed the current in the circuit EM continues to travel in the original direction, due to the back electromotive force induced in the rotor windings, previously mentioned. It is found that only a very few turns of compounding are necessary to prevent reversal.

There is no objection to the compounding turns, but the rocking of the brushes backward is undesirable, since it is likely to cause sparking when the exciter is heavily loaded.

A similar exciter reversal has been repeatedly produced by the careless manipulation of the exciter field rheostat in power station operation. Consider the machine to be running preparatory to synchronizing. Too much of the resistance in the exciter field rheostat may accidentally be cut out, due to the slow rise of the alternator voltage. Consequently, the exciter current and alternator voltage rise a good deal above the normal required for synchronizing. The exciter field resistance is reinserted to neutralize this effect, and may cause the exciter voltage to collapse rapidly. This will have a similar effect to that occurring when the exciter field is entirely interrupted, and is even more likely to make the exciter field reverse its polarity than a complete interruption in the exciter field circuit, as, at the time, the back electromotive force of the rotor windings M predominates, the polarity at the slip-rings and exciter terminals is reversed, and, as the exciter field circuit is not broken, its current reverses also, and assists to build up the exciter polarity in the opposite direction. Fig. 22 illustrates the conditions obtaining.

Sudden changes of load and sudden short-circuits also cause reversals of the field polarity of the shunt-wound exciter. Under these conditions the voltage induced in the main field circuit is several times the normal exciter voltage, and therefore passes an increased reverse current through the shunt field. The compounding fitted to the exciter overcomes the difficulties entirely.

Experience has shown that this explanation is the correct one, and that the remedies adopted are satisfactory. The author has since made oscillograph tests, which entirely confirm the foregoing remarks.

### (7) Eddy Currents in Rotors.

It has long been recognized that in three-phase turbo-alternators voltages are induced in the rotor, resulting in currents circulating in the rotor windings and body—more especially near the periphery of the latter. These voltages are induced in normal operation by flux pulsations, set up by variations in the stator current, or by periodic changes in the reluctance of the magnetic circuit. The resulting eddy currents increase the temperature of the alternator, lower its efficiency, and also, as is now known, may reach a magnitude sufficient to heat the metals to such a high temperature as to affect their mechanical properties.

The first indication of serious overheating was found several years ago when, in an alternator with a barrel rotor having a comparatively small air-gap between the stator and rotor, the coil-securing keys at the lagging edge of each pole were found to have been unduly hot. The heating was traced to the flux pulsations caused by the large ratio of width of stator tooth to length of air-gap; it was more pronounced at the lagging edge of the pole, as the flux of an alternator on ordinary loads is distorted by the armature ampere-turns in this direction, reaching a high density, with consequently increased local heating. Another difficulty is arcing. It is only comparatively recently that the voltages induced in the rotor body have reached such a value as to set up arcing. Signs of arcing were traced between adjacent sections of keys securing the winding coils in the slots, and between the spacer pieces fitted in the radial ventilating ducts on the plate type of rotor. The arcing was eliminated by the use of metal bonding-strips fitted under the keys, the centrifugal force of the coils forcing the bonding-strips into intimate contact with the keys.

Three years ago, during the annual overhaul of a large turbo-alternator, small cracks were found on the lips of the rotor caps where they were spigoted into the rotor body. This defect was found after two years' continuous operation.

A microscopic examination of the cap material indicated the presence of small amounts of slag, which, however, in themselves, were insufficient to cause the fractures. The fault developed on a water-cooled rotor. At the time it was suggested that, the body having been cooled to a greater extent than the cap, the radial clearances allowed in the standard construction of rotor without water-cooling were too small, and thus heavy stresses had been produced in the spigot of the cap. The clearance was therefore increased. After the machine had been used for a further 12 months, the rotor was again removed for inspection, and it was found that the flaws had again appeared, on this occasion distinct signs of arcing on the cap spigot being apparent. The cap material was pitted and bore traces of local heating; it had become locally brittle, and the small cracks had consequently developed. After careful investigation it seemed clear that the eddy currents induced in the rotor during normal operation were insufficient to cause the arcing, but that very heavy currents might have been induced by sudden short-circuits on the alternator.

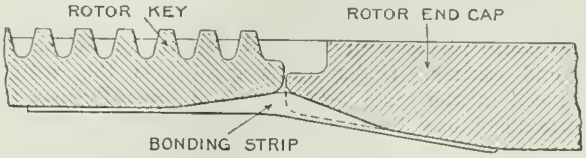


Fig. 25.

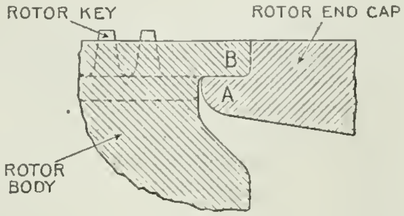


Fig. 26.

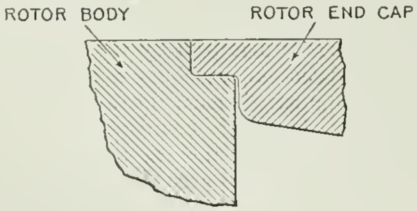


Fig. 27.

At the time this question came up for discussion, a 7 500-kVA, 6 600-volt, 3 000-r.p.m. three-phase alternator was being subjected to special sudden short-circuit and field-breaking tests at the Heaton works. It was decided to remove the rotor end caps, and to make a careful examination after the tests had been completed. The result was very convincing.

It was found that arcing had taken place between the caps and the rotor body in much the same way as

TABLE 2.

*5 000-kW Alternator, Short-circuit Tests. Rotor Volts and Current, Exciter Volts and Field Current.*

| Pressure | Compound winding | Rotor pressure | | | Exciter pressure | | | | Rotor current | | | | Exciter field current | | | | Time from s.c. to end of film |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Before s.c. | Maximum peak | At end of film | Before s.c. | Maximum peak | At end of film | Final by voltmeter | Before s.c. | Maximum peak | At end of film | Final by ammeter | Before s.c. | Maximum peak | At end of film | Final by ammeter | |
| volts | | volts | volts | volts | volts | volts | volts | volts | amperes | amperes | amperes | amperes | amperes | amperes | amperes | amperes | seconds |
| 2 000 | In | 8·5 | − 29·7 | + 3·4 | 12·0 | − 23·5 | + 3·8 | — | 25·5 | 69·4 | + 18·7 | — | 0·2 | 0·38 | + 0·05 | + 0·2 | 2·1 |
| 2 000 | In | 9·2 | − 14·1 | + 5·4 | — | — | — | — | 25·5 | 87·5 | + 35·5 | + 24·0 | — | — | — | — | 1·6 |
| 2 000 | Out | 9·5 | − 26·9 | − 7·9 | 12·0 | − 18·6 | − 9·1 | + 5·0 | 25·5 | 179 | + 30·6 | + 17·5 | 0·3 | 0·91 | − 0·25 | + 0·15 | 1·0 |
| 3 300 | In | 15·5 | − 41 | 0 | 18·5 | − 42·4 | + 1·6 | — | 42 | 256 | + 21 | + 27·2 | 0·4 | 1·09 | 0 | + 0·2 | 2·7 |
| 3 300 | Out | 15·0 | − 28 | − 16·8 | 18·5 | − 26·5 | − 21·4 | 0 | 40·5 | 378 | + 20·8 | 0 | 0·43 | Off film | − 0·60 | 0 | 1·3 |
| 5 000 | In | 23·5 | − 59 | 1·5 | 27·5 | − 36·4 | − 11·4 | + 3·5 | 64·5 | 490 | + 46·8 | + 21·0 | 0·5 | 2·04 | − 0·23 | + 0·1 | 2·1 |
| 5 000 | Out | 23·5 | − 47 | − 34·4 | 27·5 | − 39·0 | − 45·5 | Reversed | 64·5 | 725 | − 43·5 | — | 0·65 | 3·23 | − 0·93 | − 1·0 | 0·95 |
| 6 600 | In | 37 | −104 | − 18·5 | — | — | — | — | 100·5 | 930 | + 60 | + 20·5 | — | — | — | — | 1·4 |
| 6 600 | Out | 37 | − 64 | − 57·5 | — | — | — | — | 99 | 1 320 | − 73·5 | — | — | — | — | — | 1·8 |

TABLE 3.

*Rotor Circuit-breaking Tests.*

| Stator pressure | Compound winding | Rotor pressure | | Time to zero | Rotor current | | Remarks |
|---|---|---|---|---|---|---|---|
| | | At start | Maximum | | At start | Time to zero | |
| volts | | volts | volts | seconds | amperes | second | |
| 5 000 | In | 23·5 | (Off film) | >1·9 | 66 | 0·032 | Little arcing |
| 5 000 | In | 23·5 | — 245 | >1·6 | 66 | 0·004 | No arcing—clean break |
| 5 000 | Out | 23·5 | (Off film) | >1·5 | 64·5 | 0·050 | Little arcing |
| 5 000 | Out | 24·0 | — 288 | >1·6 | 67·5 | 0·060 | Little arcing |
| 6 600 | In | 37·5 | — 284 | >1·4 | 100·5 | 0·130 | Considerable arcing |
| 6 600 | In | 37·0 | — 387 | >1·7 | 99 | 0·047 | Little arcing |
| 6 600 | Out | 37·5 | (Off film) | >1·25 | 105·5 | 0·052 | Little arcing |
| 6 600 | Out | 36·5 | (Off film) | >1·7 | 100·5 | 0·065 | Little arcing |

TABLE 4.

*5 000-kW Alternator. Exciter Field-breaking Tests.*

| Stator pressure | Compound winding | Rotor pressure | | Time to zero | Rotor current | | Time to end of film |
|---|---|---|---|---|---|---|---|
| | | At start | End of film | | At start | End of film | |
| volts | | volts | volts | second | amperes | amperes | seconds |
| 5 000 | Out | 24 | — 8·0 | 0·075 | 66·6 | 53·5 | 0·54 |
| 5 000 | In | 24 | + 2·8 | — | 66·0 | 52·5 | 1·05 |
| 6 600 | Out | 36 | — 5·0 | 0·11 | 99 | 66 | 1·0 |
| 6 600 | In | 37 | 0 | 0·16 | 99 | 69 | 0·9 |

TABLE 5.

*5 000-kW Alternator, Short-circuit Tests. Voltage between Oil-thrower Rings on Rotor Shaft.*

| Stator pressure before s.c. | Peak pressure across shaft before s.c. | First peak pressure across shaft after s.c. |
|---|---|---|
| volts | volts | volts |
| 2 000 | 0·27 | 10·6 |
| 3 300 | 0·39 | 13·4 |
| 3 300 | 0·40 | 15·5 |
| 5 000 | 1·23 | 26·2 |
| 5 000 | 1·16 | 26·2 |
| 6 600 | 0·82 | 22·6 |
| 6 600 | 0·68 | 22·6 |

had occurred in the water-cooled alternator. The principal arcing had occurred between the faucet on the rotor body and the cap spigot, also, to a smaller extent, between the rotor keys and the cap spigot. This was ascribed to—and later proved to be due to—the fact that, in the rotor under test, the keys were partially insulated from the caps by varnish. It was clear that comparatively high voltages were induced in the rotor windings and body by the variations in the value of the alternator main flux caused by:—

(*a*) The variation of currents in the stator when the stator windings were short-circuited.

(*b*) The interruption of the field current effected by a quick-break switch without a discharge resistance.

The remedy may be applied to the rotor in two ways:

- (i) By short-circuiting, i.e. bonding the caps into contact with the rotor body, or by providing special short-circuiting rings at the end of the body.
- (ii) By insulating the cap from the body so that currents will not stray into them.

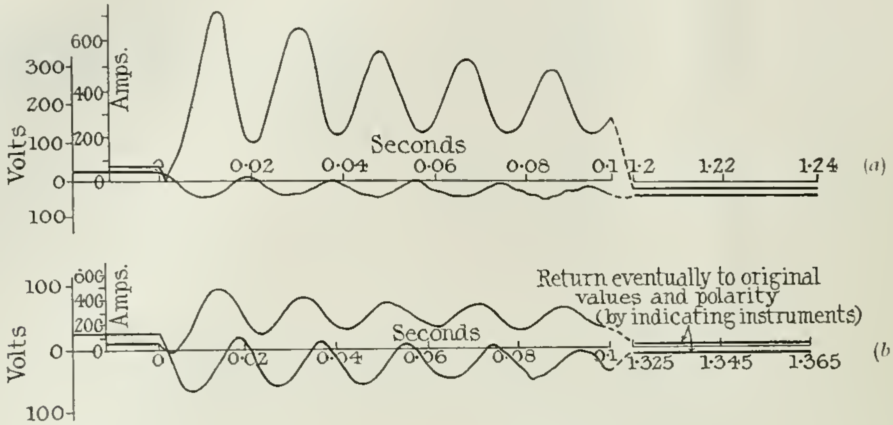


FIG. 28.—Rotor pressure and current under short-circuit conditions.
(a) Compounding out. (b) Compounding in.

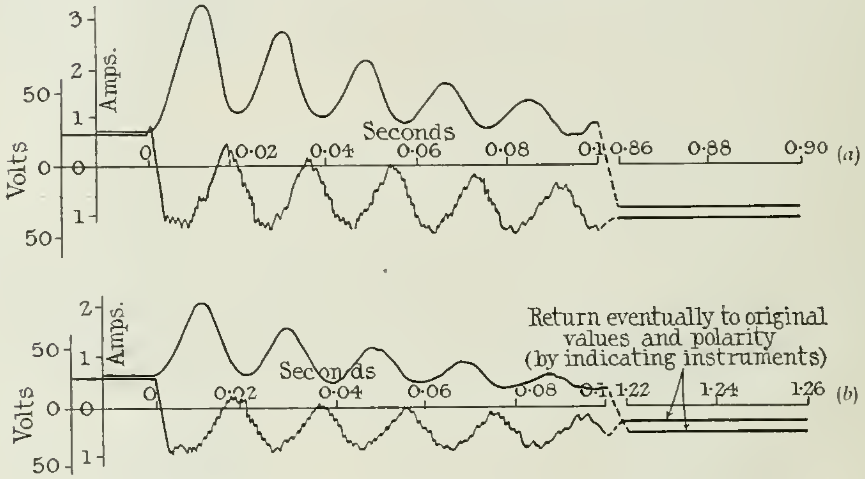


FIG. 29.—Exciter pressure and field current under short-circuit conditions.
(a) Compounding out. (b) Compounding in.

The latter remedy is the less satisfactory, and, moreover, more difficult to accomplish without radical departure from the best mechanical construction of the rotor. The first remedy was therefore adopted, and effected in a simple way by extending the bonding-strips above-mentioned from under the rotor keys to the caps. The modification was made on the 7 500-kVA alternator which had already been tested, but, as this plant was urgently required for shipment abroad and had already been considerably delayed owing to the earlier extended tests, it was not again placed on the test bed. Fortunately, an exactly similar machine was going through the shops at the time and all the tests were repeated, with the bonding-strips extended from the rotor body to the end-caps.

After a number of tests on this second machine, the rotor end caps were removed and the bonding-strips examined. A number of the strips were found to have fused at the points where the caps join the body, proving that heavy currents had been passing between the body and the cap; the caps and rotor body showed no marking.

Bonding-strips of larger cross-sectional area were then fitted, and the stator again subjected to severe short-circuit and field-breaking tests. After the removal of the caps, the bonding-strips were found to be intact, and neither caps nor rotor body showed any signs of arcing or local heating.

It is interesting to record that the two machines satisfactorily withstood more than 100 dead short-circuits during these investigations, some of which were made at 25 per cent above normal voltage.

The tests proved conclusively that, with suitable design, the eddy currents induced in a rotor during the worst conditions of short-circuit and of field-breaking can be readily carried by the rotor body, by the keys securing the exciting windings in position, and by the end-caps which support the ends of the exciting windings projecting beyond the rotor body.

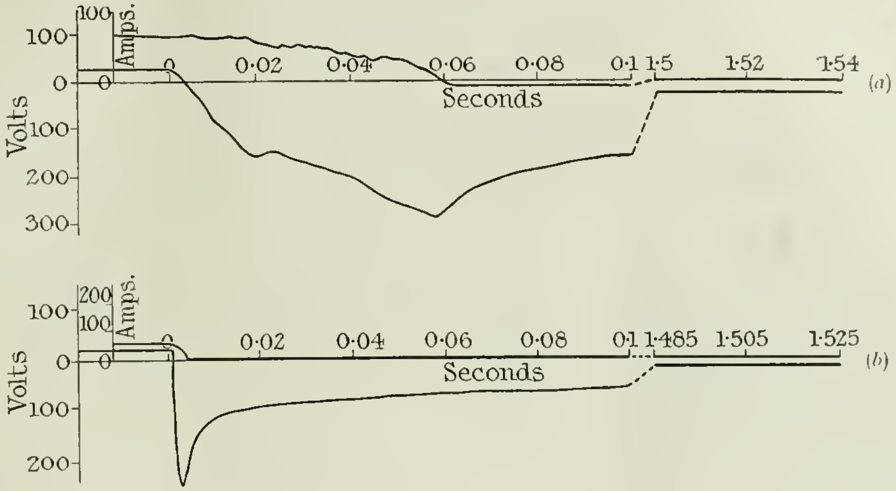


FIG. 30.—Rotor pressure and current on interruption of rotor circuit.

(*a*) Compounding out. (*b*) Compounding in.

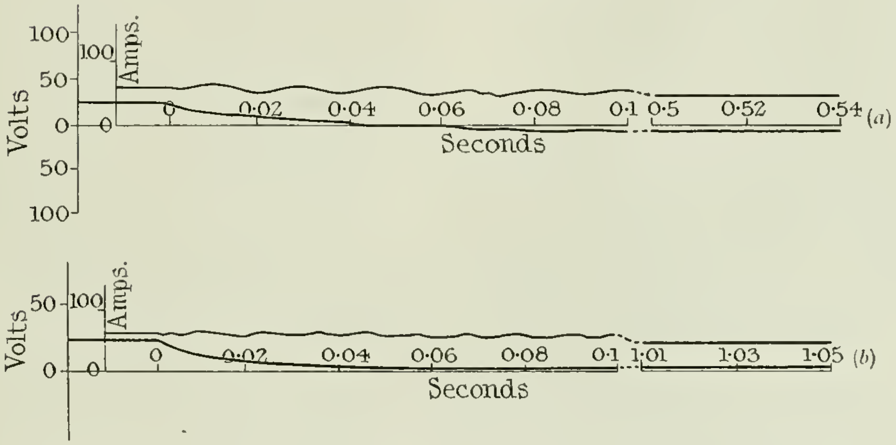


FIG. 31.—Rotor pressure and current on interruption of exciter field circuit.

(*a*) Compounding out. (*b*) Compounding in.

Difficulty is experienced, however, in transmitting these currents between the cap and the body unless bonding-strips of large cross-sectional area are used. Such thick bonding-strips are objectionable as they occupy a great deal of space which would be more effectively filled by the exciting windings. A bonding-strip was therefore designed, having a locally increased cross-sectional area to fill the clearance space between the cap and the body as illustrated in Fig. 25, the caps and keys being shaped, if necessary, to take the additional copper area.

Referring again to the large alternator mentioned on page 453, the metal of the end-cap where cracked did not break away, and the reason for this will be clear from Fig. 26, which illustrates the standard construction adopted by Messrs. Parsons. The small pieces of metal which might have been broken off by the centrifugal stresses were held by the overhanging lip or faucet B of the rotor body. The fractures occurred at A.

The author has knowledge of certain rotors designed with the caps spigoted over the rotor body, where, in addition to other damage, pieces from the cap, each weighing approximately 2 oz., had broken away and caused damage to the alternators, necessitating their being rebuilt. At the time, various explanations were put forward as to the cause of the failures, but the author suggests that they may have been due to eddy currents. This is rather confirmed by considerations referred to later in the paper.

The rotors in question were spigoted as shown in

Fig. 27, a method which is perhaps more frequently adopted, both in England and on the Continent, than that illustrated in Fig. 26, which, however, the author considers to be the best practice.

### (8) OSCILLOGRAPH TESTS.

Amongst the oscillograph tests on the 7 500-kVA, 3 000-r.p.m. alternator, the following records were made to obtain exact data of the instability of exciters, and of the voltages induced in the rotor :—

(*a*) Rotor voltage and current, exciter volts and exciter field current, with the stator windings suddenly short-circuited (see Figs. 28 (*a*) and (*b*), and 29 (*a*) and (*b*)).

(*b*) Rotor voltage and current with the main field circuit opened by means of a quick-break knife switch, without discharge resistance (see Fig. 30 (*a*) and (*b*)).

(*c*) Rotor voltage and current with the exciter field circuit broken by means of a quick-break knife switch (see Fig. 31 (*a*) and (*b*)).

(*d*) The change in voltage induced in the rotor shaft with the stator windings suddenly short-circuited. The oscillograph strip was connected to an oil-thrower ring at each end of the rotor shaft (see Fig. 32)).

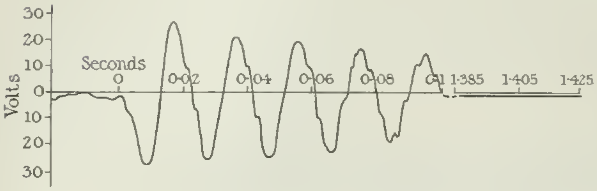


FIG. 32.—Pressure across rotor body at short-circuit.

The above tests were made with and without the exciter compounding turns in circuit.

Tables 2, 3, 4 and 5 give a short summary of the above and other tests, from which it will be seen that the voltages induced in the rotor windings on breaking the rotor circuit are very much more severe than those which occur on suddenly short-circuiting the stator windings.

It is impossible to give here complete records of the whole series of tests, but from them it was made very clear that suitably designed compounding turns fitted to the exciter poles are effective in preventing a reversal of the exciter magnet polarity when the alternator is suddenly short-circuited. This is also true when the rotor main field circuit is broken, when sudden variations are made in the exciter field circuit, or when sudden load variations on the alternator occur, as described earlier in the paper.

The author has been repeatedly requested by engineers to express an opinion upon the use of the quick-break field switch without discharge resistance in the main field circuit. In their view such a switch is essential in an emergency, in order to reduce the alternator voltage to a minimum with the least possible delay. In order therefore to obtain complete information upon this question, a series of tests were made to ascertain the conditions in the alternator when this switch is opened.

The voltages induced in the rotor windings and rotor body when the stator was suddenly short-circuited were 58·8 volts and 26·2 volts respectively. From comparison with tests (*a*) and (*b*) above-mentioned, it is reasonable to assume that the voltages induced in the shaft would be even higher than the latter figure under similar conditions on breaking the field by means of a quick-break switch. With this large potential difference between the shaft ends, it is obvious that heavy circulating currents must flow through the keys, shaft, and rotor caps.

As a result of these tests, it will be clear that, although every precaution may be taken in the design of alternators, heavy currents will circulate through the rotor on breaking the field circuit by means of a quick-break switch without discharge resistance. In the author's opinion it is inadvisable to subject the rotor repeatedly to these currents. It is recommended that the quick-break switch should be installed, but should be made to operate in emergency only, and should not be operated when tripping the alternators by hand from the busbars during normal operation. There will be no difficulty in arranging for this, and means can also be provided for testing the switch when the alternator has had its voltage reduced to a low value, or when it is unexcited.

In a paper such as this, it is possible to glance at only a few of the deductions made from experience and tests. It will be appreciated that although a great deal of work has been done to obtain more exact knowledge of what is really taking place in the operation of turbo-alternators, there is yet ample scope for research and greater improvements.

In conclusion, the author would express his thanks to Sir Charles Parsons, K.C.B., F.R.S., for his kindness in giving permission to publish the information contained in this paper, and to his colleagues on the staff of Messrs. C. A. Parsons & Co., Limited, Heaton Works, Newcastle-upon-Tyne, for their kindly criticism of the paper during its preparation.

## DISCUSSION BEFORE THE INSTITUTION, 15 FEBRUARY, 1923.

**Dr. S. P. Smith :** One of the first things that strikes the attention of a designer on reading the paper is a statement on page 441 where the author pays tribute to the courage and initiative of consulting engineers who have encouraged his firm to put in a novel type of plant which resulted in a much larger increase of output. There is nothing more helpful to designers than to have such encouragement from consulting engineers. When a consulting engineer states that no tender will be considered unless the tenderer can show plants of a similar or larger size already working, the designer becomes very discouraged. The first point about which I wish to speak is in regard to ventilation. Designers of turbo-alternators appreciate that they have here a machine through which it is possible to pass only a certain amount of cooling air. A more skilful designer may get perhaps 5 or 10 per cent more air through the air channels than a less skilful designer could, but the amount is strictly limited. Success in these large machines entails limitation of the losses. The author shows several ways in which this can be done, including a very ingenious and useful arrangement for reducing to a minimum the stator copper losses. I should be glad if he would indicate in his reply by what percentage the losses in the cable described with alternating current at 50 periods differ from those with an equivalent direct current. There is a point which manufacturers often overlook in the construction of large turbo-alternators. The weakness with the large turbo-alternator seems to lie at the present day more in the stator than in the rotor; and I do not think that sufficient attention has been paid to the elimination of hot spots in the machine. Though we try to get the factor of safety as high as possible, I think that if more care were taken in the construction of the stator core many breakdowns might be prevented. It is impossible to handle the laminations too carefully. If the shops take proper care in constructing the stator core, the iron losses in a turbo-alternator can be kept within 1 per cent of the output; otherwise they may well become 2 per cent. Large iron losses affect not merely coal consumption, that is, running cost, but also temperature guarantees and the life of the machine. Now that we use high-resistance silicon steel, we have to remember that the tools will not last so long as they did with the softer steel that was used years ago. It is absolutely necessary, therefore, to remove all rough edges round both the slots and the segments and to build a very rigid core. The author prefers to use a long core and small bore, but I think that if a larger diameter and shorter core were adopted, he might not find it necessary to use some of the special cooling devices mentioned. With regard to the rotor, it is known that when there is a hole in the centre the stresses are twice what they are when there is no hole. Is it worth while having a hole through the centre of the rotor in order to test the material and thereby get double the stresses? I think it is, but a test piece from the whole length of the rotor should be taken by cutting an annular ring. It is then possible to examine very carefully not only what the inside of the hole is like, but also the mechanical properties of the test piece. One firm has used aluminium instead of copper for the rotor winding. I doubt if a small diameter rotor would be so suitable for that purpose. Although the conductivity of aluminium is only 60 per cent of that of copper, the problem of the rotor end-covers becomes much simpler. In connection with the shape of the pressure wave, the author shows that it is possible to get a very smooth curve both between phase and neutral and between phases. Designers have long known that turbo-alternators present the best means of obtaining a practically pure sinusoidal voltage wave. There is, however, one danger which should be borne in mind. Though the tooth ripple may be too small to be seen in an ordinary oscillogram, there is a possibility of harmonics in the ripple which may cause trouble. For example, with 18 slots per pole-pair the principal harmonics would generally be the 17th and 19th. There is, however, a possibility that in addition there may be a 15th and a 21st harmonic, the danger of which is that they are multiples of three. The 17th and 19th, in a balanced system, have little effect on telephone wires a reasonable distance away, because, like the fundamental, their sum is zero at every instant; but whatever they are caused by, all harmonics, the orders of which are multiples of three, reach their maxima together; consequently when the neutral point is earthed the potential of the three lines is simultaneously raised and lowered with respect to earth, and currents can flow to and from earth at these frequencies. Therefore, where possible, the slots and winding should be arranged so as to avoid all trace of slot ripple and of harmonics, the orders of which are multiples of three. The means available for this are well known to designers.

**Mr. W. M. Selvey**: I propose to consider a few points in the author's subject, mainly from the point of view of operation. First I should like to suggest one or two details for the author's consideration. In Mr. A. B. Field's paper* which was read in 1915 this question of output was reviewed, and the question was then looked at from the point of view of kVA × $(\text{speed})^2$. Might not that be a better way of viewing the subject? A comparison of that paper with the one under discussion shows what an enormous advance has been made. There are one or two details to which I wish to refer, the first being the laminated cable. This was quite a vexed question some years ago. The result of splitting up the formerly stiff conductors was always breakages of mica at the edge of the slot when a short-circuit occurred. Probably the major improvement that has been introduced (since the benefits of laminated conductors were then well understood) is the flexible mica insulation, which is very modestly announced in the paper. The difficulty in connection with insulation is the expulsion of the air. For insulation one requires something which will conduct heat but will not conduct electricity. That in itself seems a sort of contradiction in terms. Air, however, which is an extremely bad conductor of heat for various reasons, becomes at times a good conductor of electricity. I should like to hear whether there are any possible developments in this direction by the use of the newer types of insulation which are being made, I think, from solidified colloids. It seems as though some of these new types of insulation may entirely replace mica. The dielectric strength is quite good and they certainly have a more mechanical nature. Curiously enough, the difficulties in operation arising to-day are generally due to current. Anything which decreases current, whether in a cable or machine, is of assistance. I am surprised that more use has not been made of the information given by Mr. Welbourn in connection with his visit to Italy, with regard to the very successful alternators which have been running for four or five years generating current at 30 000 volts. That increase of pressure will, of course, diminish very greatly the amount of copper used.

---

* "Some Difficulties of Design of High-speed Generators, *Journal I.E.E.*, 1915, vol. 54, p. 65.

On page 447 there is another small point requiring elucidation with regard to the two power stations a mile apart. A discussion is wanted on that subject; it is a question of distance and earth resistance. How far apart are linked power stations to be put before one must earth both? I have that actual problem before me at the present time. There must be some limiting distance. If one goes far enough the earth resistance will be high. I suggest that the solution in some cases may be the earthing of one station through a limiting resistance and arranging an automatic switch so that any rise in pressure at that station which shows that it has become disconnected from the other station, shall cause any limiting resistance to be short-circuited. It is news to me that circulating current, which is wattless, influences the ordinary induction type of meter. One can quite understand an ammeter giving a higher reading, but this case is stated as a definite transference of "load," and I cannot understand the ordinary integrating meters in the power station showing transference of load due to circulating currents. On page 449 there is the statement: "In this type of filter (wet-air) it is possible not only to clean the air, but also to lower below that of the surrounding atmosphere the temperature of the air entering the machine." That is only possible when the air is being drawn from the engine room and the water is at the temperature of the outside air; but is this generally the case? It is quite a number of years since it was considered good practice to draw air from inside the engine room, because that air is generally laden with oil vapour. The latter caused serious trouble and the breakdown of a very large machine in the North due to accumulation of oily mud on the windings. I have made many experiments on the subject, and I have been unable to find any appreciable air-cooling or humidity effect when the air and water are at about the same temperature. It is very difficult to obtain any increase of humidity by simply forcing the air through a spray. If humidified air is required, steam must be added to it. I think, therefore, that the statement made by the author ought to be further investigated. I have made a large number of experiments on the carrying-over of water, and I probably obtained hints from the author's work. In an air-filter with which I experimented, I could alter the quantity of air over a large range. By means of winding a coil of ordinary double cotton-covered wire on a conductor, placing it in the filter outlet and then noting the insulation resistance, it was perfectly easy to see if and when water came over from the filter. The author has not mentioned the very interesting fact that in these large machines with long rotors and parallel ducts the pressure necessary to force the air through the alternator has been much increased. In the early days it was something under 1 inch head of water. Then it increased to 3 inches and 6 inches, and I have been informed that in some cases it may be increased to 15 inches, so that its provision becomes a serious matter. From that point of view, I am entirely in agreement with the author that it is necessary to pay attention to the efficiency of pumping the air, and that it can only properly be done by an external fan. As regards the water cooling and the deductions made from it as to heat losses in the rotor, I feel that only a small proportion of the heat from a rotor coil can be removed by a tube immediately underneath it, and a good deal of the heat must in any case be dissipated from the surface of the rotor. Although the author is guarded in his remarks, he commits himself to certain figures. In any case it must be remembered that the chief heat resistance is in the mica windings, and the fact that the bottom of the slot is cool is no guarantee whatever as to the copper temperature. It seems that there is something rather doubtful in the conclusion at which the author has arrived with regard to the field-suppression switch. Must we suppress the field for the purpose of limiting the voltage on short-circuit, and thereby injure the rotor? It seems to me unsound to have an emergency switch which must not be used on ordinary occasions, because its use will produce damage. If there is anything in the apparatus or plant which can be damaged at the will of the operator it should be altered.

**Mr. G. W. Partridge**: I should like to know the author's opinion regarding the limit of pressure on such a machine as he describes, running at 3 000 r.p.m. with an output of 25 000 kVA, which is referred to in Table 1. Of what class of metal are the rotor caps mentioned at the foot of page 442 made? In many respects most of the troubles enumerated by the author are of long standing and have been overcome by contractors in the present-day design of such machines. The company with which I am associated has supplied single-phase current to the Brighton Railway for the past 14 or 15 years, and many of the troubles to which the author has referred, particularly those connected with the rotors, were experienced by my company, but the difficulties have been overcome by the designers of the generators. I think the author will agree that a single-phase supply to a railway, accompanied as it is by a great number of direct short-circuits, is a very severe test for any a.c. machine. It might be desirable in the future to subject a.c. generators to a test of a limited amount of single-phase current with the object of deciding whether the rotor defects referred to in the paper actually take place. In the design of stator illustrated, which shows straight conductors in use, twice the number of joints would have to be made in such stators as compared with straight conductors with the bent ends used by other contractors. With regard to the circular laminations, I should have thought that rectangular bars, made up in a certain way to be practically free from eddy currents, would have been a very much stronger proposition. Referring to the stator in Fig. 11, it seems that the overhang of the coils is excessive and would certainly be reduced if the design of straight bar with the bent end were used. Another important point in connection with Fig. 11 is that the coils are not supported where they leave the slots. This is, I think, very important. With regard to the tunnel formation of winding, this is really a reversion to an old system and seems to possess certain disadvantages. First, the large number of joints to which I have already referred, and secondly, the difficulty of getting a good fit between these bars and the stator so as to overcome the difficulty of the air space round the coil, which would in turn cause a brush discharge difficult of elimination and likely to give trouble. In the construction shown the bars would have to be driven in from one end of the stator. Another point is that if any short-circuit or welding took place between the copper and the iron it would be absolutely impossible to get at the coils or even to examine them without dismantling the whole stator. I entirely agree with the author that it is a very difficult matter to design a machine and make ample allowance for expansion of the copper in both the rotor and in the stator. In fact, in a modern high-speed machine it is more difficult to keep the copper inside the insulation than it is to keep the current. In Fig. 11 there appear to be no through bolts for holding the stator iron. From my experience it is necessary that such bolts must be used if the core is to be held rigidly. Of course the nearer the through bolt is to the flux the more rigid the stator can be held, from a mechanical point of view. On the other hand, the nearer the through bolt is to the flux the greater the trouble due to eddy currents, from an electrical point of view. We have machines with such through bolts of non-magnetic material insulated by mica from the core plates, and these have been running quite satisfactorily as either single-phase or three-phase generators for about 8 to 10 years. The separate motor fans shown by the author are, I think, another weak link in the generator system. There are enough weak links already, as we know to our cost; and as the fan will probably be running at the same speed as the generator, i.e. 3 000 r.p.m., I cannot see much advantage in having a separate fan. I am in agreement with the author that the closed air system is preferable for large machines. I should like to ask him if he has ever considered two-part stators, in which the joint might be at right angles to the path of the magnetic flux. It seems that such a machine would possess some advantages, particularly when, owing to the high speed, such machines are of great length. Eddy currents in the rotor are an old trouble, particularly in single-phase work. Even in three-phase work one often meets with it when a short-circuit occurs between any two phases. On more than one occasion I have seen rotors of three-phase generators broken down through this cause. The provision of bonding strips fitted under the rotor keys has been more or less in use for a great number of years. In such a construction it is, of course, necessary to allow ample room for expansion. As regards the general design of rotors for these high speeds, it seems to me that the manufacturers have studied the design of the stators more closely than that of the rotors. In the old days when four-pole and six-pole machines were in use the rotors very seldom went wrong, and it was nearly always the stator which developed the fault. The following precautions should be taken in the design of these high-speed rotors: (1) The movement of the field coils should be limited as much as possible and every precaution taken to prevent damage to the insulation caused by movement either from centrifugal force or expansion; (2) any bonding strips or short-circuiting rings should be given room for expansion; and (3) the insulating blocks holding the end-coils in place should be of a material which cannot shrink or warp due to heating. With regard to the author's remarks on page 453 as to the reversals of field polarity in exciters when the generator is short-circuited, about 9 years ago I showed the effects of a large number of short-circuits on alternators. These effects were: (1) The excitation voltage was reversed; (2) the field current was increased about $2\frac{1}{2}$ times; (3) the presence of alternating current in the field; (4) this alternating current was of twice the periodicity of the main current. Very little trouble has been experienced due to exciter instability, probably because special care was taken to saturate the pole shoes at low excitation, thereby giving to the exciter characteristic the proper shape and curvature.

**Dr. W. M. Thornton**: One of the most interesting things in the paper is the wave-form of the 18 750-kVA generator (see Figs. 12 and 13). Those who have had experience in taking wave-forms over a wide range of machines know how difficult it is to obtain and maintain a sine wave on load. These are the best I have seen for a large machine. The problem most prominent at the present time before those responsible for large units is how best to kill the rotor field after a short-circuit, or for any other purpose. An important paper by Mr. R. E. Doherty on "Exciter Instability" appeared in the *Journal of the American Institute of Electrical Engineers* (1922, vol. 41, p. 731). The best remedy so far is to compound the exciter, and the oscillograms of Figs. 28 to 31 show how useful this is. There is a further remedy which does not appear to have been tried, that is, to use a small buffer resistance in series between the rotor field and exciter. The object of this is to prevent the voltage induced in the rotor circuit by the stator ampere-turns from reaching the exciter terminals and so reversing its field. If the exciter pressure is, say, 25 volts and the rotor current 65 amperes, the resistance of the circuit is 0·38 ohm. On short-circuit the rotor current rises to a mean value of 300 amperes with the compounding turns in circuit. The rotor voltage is therefore $(300 \times 0{\cdot}38) - 25 = 89$, if the exciter terminal voltage does not rise. If now a resistance of $89/300 = 0{\cdot}29$ ohm had been in circuit, all the induced rotor voltage would have been absorbed in that. There would have been no undue rise of pressure on the exciter and no tendency to reversal. Such a resistance would mean that the normal voltage of the exciter would have

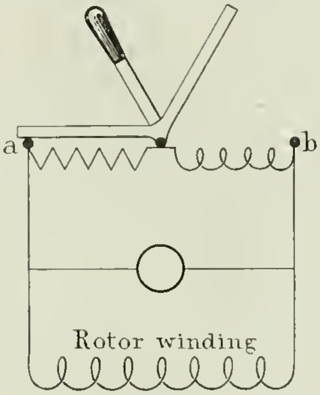


Fig. A.

to be 65 (0·29 + 0·38) = 43·5 for the same rotor current. There would be a constant additional loss of $0 \cdot 29 \times 65^2$ = 1 220 watts if the resistance has to be kept permanently in circuit. Whether this is worth losing is a question for the supply company and not the designer. The author discusses the effect of breaking the exciter field instead of the rotor circuit, but there is no need to break it. An old arrangement would seem to be suitable here (see Fig. A). If the exciter field is connected not to the terminals directly but to a change-over switch, all that is necessary to kill the rotor field is to short-circuit the exciter field by throwing the switch over from a to b. The field then dies down in about 0·07 to 0·10 second. The non-inductive resistance then provides an alternative path to the armature and lessens the vicious momentary sparking which occurs at the commutator. In this case, however, compounding turns on the exciter would prolong the effect. I should like to emphasize the great improvement that has been made of late years in the mode of bringing out the end connections on the stator so that a machine of the largest size can be short-circuited without any ill effects. I recently had occasion to take part in the preliminary tests on the short-circuit behaviour of a 6 000 kVA Parsons generator. We made nearly 100 dead short-circuits at all excitations with the sole effect of clearing the machine of dust. This led me to make the suggestion in the discussion on Mr. Kuyser's paper that the best way to free modern generators from dust in the ventilation ducts is to short-circuit the machine deliberately at reduced excitation. Instructions might be given to short-circuit each machine on some Saturday once a month, say No. 1 machine at 12.30 when the load comes off, No. 2 at 12.45, and so on. I think that the time is not far off when this will be a serious proposition at any excitation. It could be safely done with any recent Parsons machine of the same construction, and the author's 100 short-circuit tests on two 7 500 kVA machines show that the machine on which we experimented was not at all unusual.

**Mr. H. W. Taylor:** In regard to machines made by the firm with which I am associated, developments have been in some cases almost parallel with, and in other directions divergent from, those of the author. Almost parallel development has resulted from our both adopting an ideal of using the best materials, but at as low a stress as possible. This has led at higher speeds to machines with relatively small diameters and long lengths. This again has given rise to problems of ventilation; on rotors water cooling has been tried and in stators radial ventilation in compartments has been adopted. The arrangement for water cooling has, however, been slightly different from that shown in Fig. 19. Fig. B shows how passages have been provided by small holes drilled some little distance below the winding slots. In the long rotor in which this scheme was tried the holes were drilled with no difficulty by a firm of experienced gun makers. This construction admits the use of the deepest possible slot containing the largest possible amount of active material, the holes being placed in the central core of the rotor where the stress is relatively low. Fig. C, showing the method of ventilating a large 3 000 r.p.m. alternator when used in conjunction with an air cooler, may be compared with Figs. 16 and 18 in the paper. In machines of this character, auxiliary fans are necessary. Fig. C shows that the hot air from the machine is conducted through ducts in the foundations to the external fan, which, because of its inefficiency, adds further heat to it. The cooler is placed between the fan and the air opening to the turbo-alternator, so that the air enters the alternator at a temperature as low as is consistent with the temperature of the water in the cooler. A feature in which development has been divergent from that of the author is in regard to the form of the stator windings. The type sometimes described as the two-layer basket form of winding has been developed and used continuously since the building of turbo-alternators was commenced many years ago. It is felt that in this type of winding, diagrammatically indicated in Fig. C, the shape and position of the end coils are such that no appreciable stresses are produced during short-circuits, with the result that these windings require a minimum amount of supports and clamps. In regard to switching on the rotor circuit, the following points seem to me briefly to sum up the situation: (1) If the rotor field circuit is opened while the machine is under normal operation, there is undoubtedly a high voltage-rise in the windings. (2) Normal service does not require the rotor circuit to be thus suddenly opened, and can be met by withdrawing the source of supply in other ways. (3) When the stator windings are short-circuited, it is possible to open the field circuit suddenly without an increase in voltage in the rotor windings, because the short-circuited stator windings are in good mutual induction with the rotor windings. (4) Under these circumstances, although the rotor current quickly disappears, the current in the stator winding fault is not immediately suppressed, as the

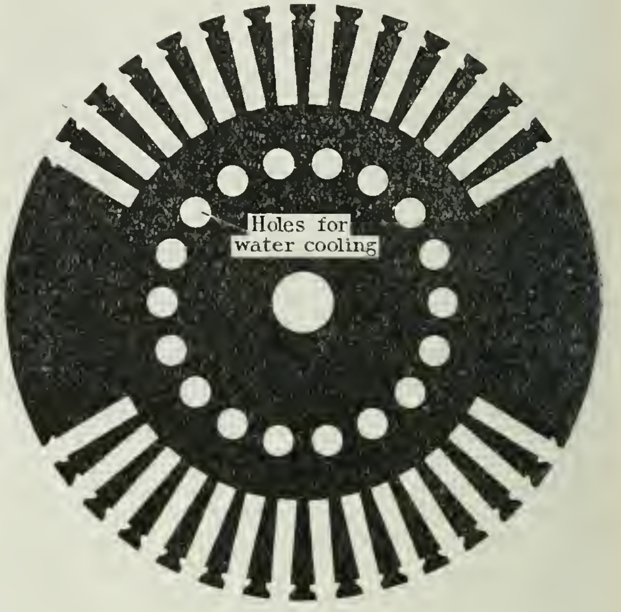


Fig. B.

flux of the machine is maintained until the stored energy represented by it has been absorbed in the short-circuited stator windings. The opening of the rotor circuit, therefore, does not simultaneously suppress the fault. (5) This being so, a scheme which withdraws the source of supply from the rotor circuit without opening it would seem to meet the conditions for both normal and emergency operation. A switch which effects this by short-circuiting the slip-rings has been developed and has already been described and illustrated in the *Journal* (1922, vol. 60, p. 773).

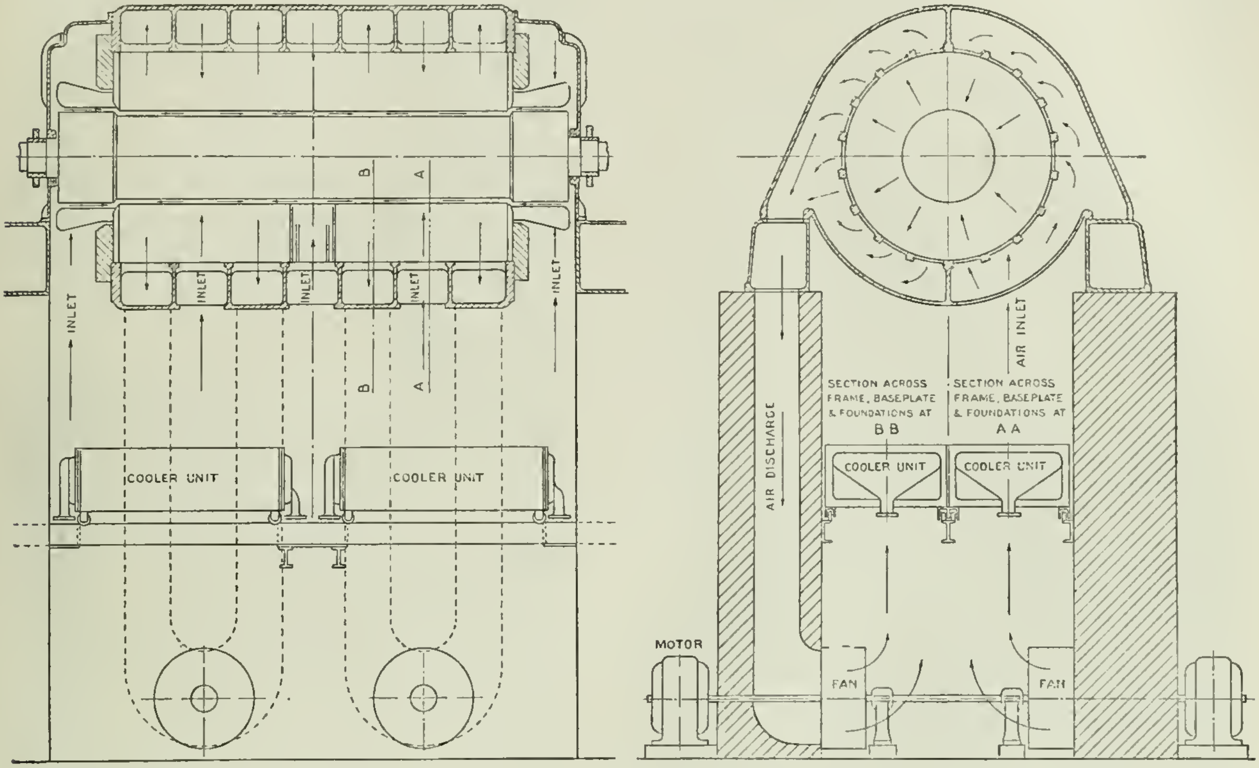


FIG. C.

**Mr. N. B. Hill** (*communicated*): In Section 4 the author suggests that there is a marked increase in inherent reactance to be expected from the use of closed stator slots. This is probably correct while considering the reactance at the normal current of the machine, but as the iron bridge would become saturated with a stator current much lower than the instantaneous short-circuit current of the machine, the maximum advantage of a closed slot over an open slot appears to be that represented by the extra leakage flux corresponding to the saturation value of the iron. In one or two cases that I have calculated, this has meant that the increase to be looked for in the reactance on instantaneous short-circuit due to the use of a completely closed slot is only of the order of $\frac{1}{3}$ per cent. When using a quick-break field switch, the author anticipates (see Section 8) the production of a voltage between shaft ends similar to that shown in Fig. 32. If the outboard pedestal is insulated the only currents which can flow in the rotor are those tending to maintain the alternator flux, and it may be an advantage to consider these from the point of view of the energy available. If the field switch is opened without a discharge resistance (really an infinite discharge resistance) the whole of the stored energy of the magnetic field is dissipated as heat in the rotor body, the amount of energy available in the case of a 15 000 kVA 3 000 r.p.m. machine being sufficient to melt about 4 or 5 cm$^3$ of copper originally at the working temperature of the machine. When using a discharge resistance the energy is dissipated as heat in two circuits in parallel, the rotor winding and discharge resistance forming one circuit, and the rotor body, wedges and end caps the other. The energy will divide between the circuits inversely as their resistance. Mr. Kuyser * gives the equivalent resistance of the rotor body circuits as five times that of the field winding, and I have confirmed this figure by a different method of measurement. If we therefore short-circuit the slip-rings (zero discharge resistance) it would appear that only one-sixth of the stored energy of the field would have to be dissipated in the rotor body circuits. Although the question is not so much one of total loss, due to the circulating currents, as of the local loss at the junction of the rotor body and wedges with the end caps, I think it is well to keep the total loss in mind, and I agree with the author that it is good policy to use the quick-break switch without discharge resistance in cases of emergency only. If this switch operates only when the protective gear operates, and the alternator field is normally destroyed by opening the exciter field switch, we ensure the quickest possible destruction of the field under fault conditions without normally subjecting the rotor to more severe conditions than would be obtained by short-circuiting the slip-rings.

---

* "Protective Apparatus for Turbo-Generators," *Journal I.E.E.*, 1922, vol. 60, p. 761.

**Mr. J. H. Shaw** (*communicated*): On pages 449 and 450 some useful information is given regarding the use of closed-circuit coolers, and the author refers to the pioneer installation at the Battersea Electricity Works. I do not think, however, that sufficient credit has been given to the patentee, Mr. Thompson, of the Battersea Electricity Works, for this achievement, and I think that few engineers know how successful this plant is in operation. It was designed early in 1918, before the plant at Blaydon, and has to-day many advantages over similar systems with which I have compared it. Some years ago I inspected the plant at Battersea and was informed that when planning the installation of their 5 000-kW alternators they could not find space for dry air-filters, and were not kindly disposed towards the wet type on account of the risk to the insulation of the machine. The chief engineer, together with his chief assistant, Mr. Thompson, set to work to devise some alternative system of cooling, and they conceived the idea of continually circulating the enclosed air, thus avoiding any filtering whatever, and using the condensate as the cooling medium, thus eliminating any necessity for cleaning the tubes. Several large makers of alternators to whom this system was explained considered it was not practicable, and as the necessary data for designing the apparatus were not available Mr. Thompson constructed experimental plant for the purpose of ascertaining the air and water velocities, tube spacing, etc. The Battersea design, as regards construction, compactness and efficiency, has justified the trouble taken, and is protected by letters patent. Practically all the cooling is effected by the condensate, the cold "make-up" water only being introduced on heavy loads or when the vacuum is poor. The cooler has been in service continuously for about four years and has not yet had to be cleaned; this would not have been possible with circulating water as the cooling medium. The working of the plant has not been interrupted, and the cooler efficiency has been maintained. Apart from this, the heat is recovered from the ventilating air, resulting in the condensate temperature being raised about 11 degrees F., which amounts to nearly 1 per cent of the total heat in the steam. The cooler was constructed to the Battersea design by Messrs. Babcock and Wilcox with plain tubes expanded into headers, sectionalized so as to reduce cost of manufacture and for ease of transit and erection, and mounted on rollers to facilitate removal if required; it has remained perfectly watertight since erection, thus dispelling any fears as regards water leakage into the air space. Another good feature of this system which will appeal to the operating engineer is the provision of thermostatically-operated air doors which permit of the alternator being cooled from the outside air should the enclosed air reach a predetermined temperature due to any cause other than electrical faults in the machine, in which latter case these air doors will remain closed. In the description of other systems it is stated that a horn or whistle will be blown and coloured lights displayed, but it is better to do this work automatically and remove the human element, especially as one knows that when things go wrong there is plenty of work for the operatives to attend to, and one does not wish to add further noise and coloured lights. It is of interest to note that the five 40 000 kW sets at Gennevilliers are cooled on the same system as that used at Battersea, and with coolers of similar design, and on account of its economy and efficiency this system is being adopted in connection with many other large plants. It is very pleasing to note the absence of noise due to the alternators being entirely enclosed, and the temperature of the engine room is more comfortable for the operatives, particularly during the summer time. I understand that the letters patent referred to cover the use of gases which will not support combustion and which at the same time improve the efficiency of the heat transmission, and I believe that experiments are being made with carbon-dioxide gas. I feel that Mr. Bond and Mr. Thompson are to be congratulated on their courage in designing and installing this cooler, and that due publicity should be given to their pioneer efforts.

**Mr. J. Shepherd** (*communicated*): The paper gives a clear statement of the difficulties with which designers have to contend, and a brief review of many different attempts to overcome them. All credit must be given to the earnest desire of manufacturers to produce sound and satisfactory machines, but when all these efforts have been made the fact remains that turbo-alternators are not as satisfactory as either makers or users desire. Messrs. Parsons and Co. are the pioneers of water-cooling applied direct to the body of the rotor, and the British Thomson-Houston Co. are now manufacturing rotors similarly cooled. Indirect water-cooling of the ventilating air is becoming universal. If water-cooling is to be accepted as necessary, the general design of turbo-alternators should be considered from a new view-point, as other inherent difficulties can then be solved at the same time. With air-cooling, the stator and rotor cores must be constructed with numerous air-passage ways, and these of necessity result in a weak structure with weakly supported stator teeth and coils. Let any engineer examine and consider the deplorable mechanical weakness of a thoroughly laminated stator coil as now constructed, various examples of which are shown in Fig. 8 of the paper. The component parts are held together only by the insulation surrounding them, and, due to the method of stranding, there must be slackness between the parts, with continuous vibration due to the alternations of current, resulting in the gradual disintegration of the insulation. Further, all the mechanical forces from the turbine must be transmitted by the insulation, which must also withstand the tremendous hammer-like blows on short-circuits. The same remarks apply, of course, to all laminated bars. As strength cannot be obtained within the coil it must be applied without, and the logical solution is a winding slot continuous throughout the entire length of stator windings including the end connections, and this positive and continuous support can be given if the water-cooling be applied directly instead of indirectly. When this is done the stator structure can be solidly constructed with the equivalent of solid rotor teeth, thus eliminating the trouble which the author and other designers have experienced from cut and broken teeth. Adequately strong supports, in the shape of cooling devices with separate and adjustable water supplies to each, give a ready and definite means, which at present we hardly possess, of detecting local heating. On the other hand, we require most positive assurance that we possess means of constructing the water-cooling devices without risk of water leakage. The internal water pressures in the rotors are usually approximately 800 lb. per sq. in. and upwards, and both Messrs. Parsons and the B.T.H. Co. successfully constructed water-cooled rotors for these pressures. The cooling devices in the stator would be subject to internal water pressures under 100 lb. per sq. in., and we possess methods of welding and electrical deposition of metals which would allow any desired thickness of metal to be built up at the joints, the only parts which need give anxiety. All the present papers by turbo-alternator designers lay stress upon the difficulties with which they must contend, and to me they clearly demonstrate the limitations of air-cooled machines and the need of an entire change of design to allow mechanically strong machines to be constructed. The problem is by no means one of air-cooling versus water-cooling, but the ever-pressing necessity of building robust and more reliable alternators.

**Mr. J. Rosen** (*in reply*): I agree with Dr. Smith that every attention should be paid to limiting the losses in turbo-alternators, and to improving the ventilation. The actual additional losses due to the eddy currents in the helically stranded conductor are extremely low, being less than 1 per cent of the $I^2R$ loss for the equivalent direct current. As far as the core is concerned, makers are fully aware of the precautions necessary in the building of a stator core, and every practicable care is taken.

I cannot agree that short rotors with larger diameters and therefore higher peripheral speeds are preferable to long rotors running at well-tried peripheral speeds, as the stresses in the former are increased beyond those which experience has proved safe.

In the past, axial holes have been trepanned throughout the whole length of the central axis of alternator rotors for the purpose of testing the material, and in some machines the metal removed was weighed to make sure that no blow-hole or clink was present. In every rotor where such a hole is drilled, the surface of the bore is carefully inspected for flaws, by means of special optical arrangements.

Theoretical investigation of the simplest case of rotational stress—namely, in a thin, flat disc—indicates that a pinhole at the centre makes the hoop stress at the periphery of the hole double what it would be at that point if there were no hole. In practice, however, there is evidence that a small hole through the centre of a rotor shaft has no such extreme effect upon stress distribution, but modifies it to a much less extent than is indicated by purely theoretical consideration. It can be taken for granted that the material will yield to some extent and ensure that the stresses become more uniformly distributed, so that the final maximum stress (in the neighbourhood of the hole) will not be actually very much greater than that in a shaft without the hole. In fact, in view of the difficulties which have recently been experienced on alternators in this direction, engineers are now asking for holes to be drilled in the centre of the high-speed shafts for the reasons above mentioned. I have recommended this procedure for large shafts since 1914, and it has been adopted in Parsons alternator rotor shafts intended for peripheral speeds in excess of about 350 ft. per second.

The slides shown by Dr. Smith are interesting, but a parallel cap for supporting the rotor windings can be obtained with a rotor running at a lower peripheral speed without having to resort to aluminium for the windings; in such a design there is no necessity to have the steep taper on the cap. The use of aluminium for the rotor windings has been a subject of peculiar interest to designers of high-speed alternators, but up to the present time its use has not proved a commercial proposition. The difficulties due to harmonics in the wave-form are appreciated, and, as indicated by the typical examples in the paper, this question has been thoroughly investigated.

In reply to Mr. Selvey, the flexible insulation has been used now for the past 10 years with unqualified success, but investigations are continually going forward to improve this insulation and to provide an even better solution of the insulation problem. A description of the investigations into the qualities necessary for insulation suitable for high voltages and for use in turbo-alternators would provide sufficient material for a separate paper, and could not be dealt with as fully as I should have liked in this paper. I have experienced no difficulties with the breaking of the mica at the edge of the slots when short-circuits occur; and with the design in question there is no tendency for the conductors to separate on a heavy short-circuit and burst the tube. I have dealt with the other questions on insulation in reply to Mr. Partridge.

Mr. Selvey appears to be under some misapprehension on the question of the cooling of the air passing through wet air-filters. As a rule in this country the air before entering the filter is not saturated, the humidity being generally in the neighbourhood of 70 per cent to 80 per cent. After passing the air filter the humidity is increased to from 90 to 94 per cent, which means that the air in passing through the filter absorbs moisture. The temperature of the remaining water in the filter is reduced by the partial evaporation, and, as the unevaporated water is recirculated, its temperature would continue to diminish and is only prevented from doing so by the heat abstracted from the incoming streams of fresh air. For given conditions, a state of equilibrium is soon reached. This was demonstrated repeatedly on tests carried out over a period of three or four years on filters situated in different parts of the country. In the example mentioned, the air was drawn from outside the engine room.

With regard to high-voltage alternators, I am aware of the 30 000-volt machines which are in operation in Italy, but I understand that some difficulty has been experienced in their operation. High voltages have already received consideration in this country, and I think that if power engineers wish to have machines which generate direct at the higher voltages, and are prepared to submit their proposals and to accept some portion of the responsibility, manufacturers would be prepared to undertake construction in this direction, at any rate in the case of machines of the largest output.

I did not propose to deal in the paper with the question of earthing alternators. As Mr. Selvey states, this is a question for very lengthy treatment, but the example was given to illustrate the injurious effects of the harmonics in the wave-form setting up high-frequency currents through the star point.

With the scheme of ventilation as described in the paper, the air pressure has been reduced to 4 inches (water gauge), and this figure includes the drop in a normal length of duct and in the air cooler.

Mr. Selvey appears to be uncertain as to my conclusions on the breaking of the alternator main field. I should explain that it is proposed to operate the main field switch (without discharge resistance) in emergency only, that is, in case of a breakdown on the alternator or for any other similar reason. It is therefore opened only when the protective relays operate, and not when the main alternator switch is opened by hand. Manufacturers are now prepared to provide the protective apparatus to function in this manner. There is no necessity to open the main field switch during the normal operation of the plant, while the alternator is fully excited.

In reply to Mr. Partridge, the limit of pressure for alternators of which there is experience available in this country is 13 000 volts. Several machines have been in operation (some for over 12 years) with satisfactory results, so that with the 25 000 kVA machine at 3 000 r.p.m. there would be no difficulty in dealing with such voltages. The end caps for supporting the rotor end-windings are made of nickel chrome steel, which has been in use since 1912, and its qualities have been gradually improved. The percentage of nickel is 3½, and the percentage of chromium less than 1.

The sketch of the stator windings in Fig. 11 in the paper is simply a diagram for illustrating the type of joint; the packings for the support of the windings have been purposely left out for clearness. In the designs described, packings are provided in the windings, and supports are provided for the conductors where they leave the slots. Such windings have been subject to the most severe short-circuits and have withstood them without being disturbed.

The multiple joint avoids the use of several parallel paths through the alternator where a heavy current has to be carried. Where two joints are used on one core conductor to connect to the end connectors, it would probably be necessary on other types of windings to use four or more parallel paths completely insulated one from the other, with a correspondingly increased number of joints. The round strand is preferred as being the most suitable construction. With round wires the danger of the primary insulation on the individual wires being damaged is reduced to a minimum. With the use of rectangular strip in the laminated construction of conductor, there are inherent difficulties which have been dealt with in earlier papers.* Apart from the mechanical difficulties, the losses in such a design of conductor, due to the unequal distribution of current, are not eliminated. The completely stranded cable described in the paper provides the complete solution of this difficulty.

The windings with tunnel slots, in practice, have proved equally or more accessible than with open slots. In the design adopted with the tunnel construction, where a fault has occurred it has been found possible to replace the windings and repair the damaged core without disturbing the other parts of the stator. No difficulty has been experienced in getting rid of the air space round the conductors, and in preventing the brush discharge. This question has been given careful consideration, with most satisfactory results.

Mr. J. S. Highfield made reference to these difficulties in a short contribution to the *Electrician* † in 1905. The remedies which were then suggested have been found to be equally applicable to present-day machines. The sides of the slots are made as smooth as practicable and are coated with insulating varnish. Protection is given to the conductors, when being drawn into position, by special insulating liners. With the flexible insulation there are a few simple workshop precautions to be taken in the assembly of the conductors in the slots, but any one bar can be readily replaced without disturbing the remainder of the windings or the insulation. The flexible insulation, besides having advantages in other directions, allows for the necessary expansion and contraction, without danger of rupture. As regards through bolts for holding the stator core, experience has proved that tight cores can be built without them.

Mr. Partridge suggests that the stator should be split transversely, in order to shorten the length of core supported by such bolts. Presumably, there would still be only one rotor, otherwise it would be equivalent to putting two alternators in tandem. The idea naturally arises in the mind of designers when having to contend with difficulties of the long machine, but such complication has not up to the present proved necessary. Mr. Partridge raises objections to the use of the separately driven fan. This can be readily fitted to an extension of an auxiliary pump motor, an arrangement which would eliminate the necessity for an additional motor. Fig. D shows the fan fitted on an extension of the extraction pump motor shaft on a 12 500 kW set, running at 3 000 r.p.m. It will be seen that the lay-out is very simple. The speed of the fan, as a rule, does not exceed 750 r.p.m., and is lower on the larger machines. I have had very wide experience with the use of the separate fans, and no serious difficulties have arisen on any of the plants on which they have been installed. With the separate fan there is an improvement of 1 per cent in the efficiency of the alternator, over that of the alternator fitted with fans on the rotor. This figure allows for the power taken by the fan motor.

---

* See, for instance, *Journal I.E.E.*, 1920, vol. 58, p. 128.

† *Electrician*, 1905, vol. 54, p. 573.

The difficulties of supporting the rotor end-windings, those due to expansion, and the danger of side slip, have all been investigated. Special packings of asbestos cloth and synthetic resin are now manufactured, which have proved satisfactory for the comparatively low voltages at which the rotors are operated.

Dr. Thornton's remarks are of interest. The tests on stability which I have given in the paper have extended over several years, but I have only recently been able to put together the results in a complete form. The use of a permanent resistance in the rotor circuit will increase the main field losses, so that it would have the same effect as the main field regulator, and is subject to the same objections.

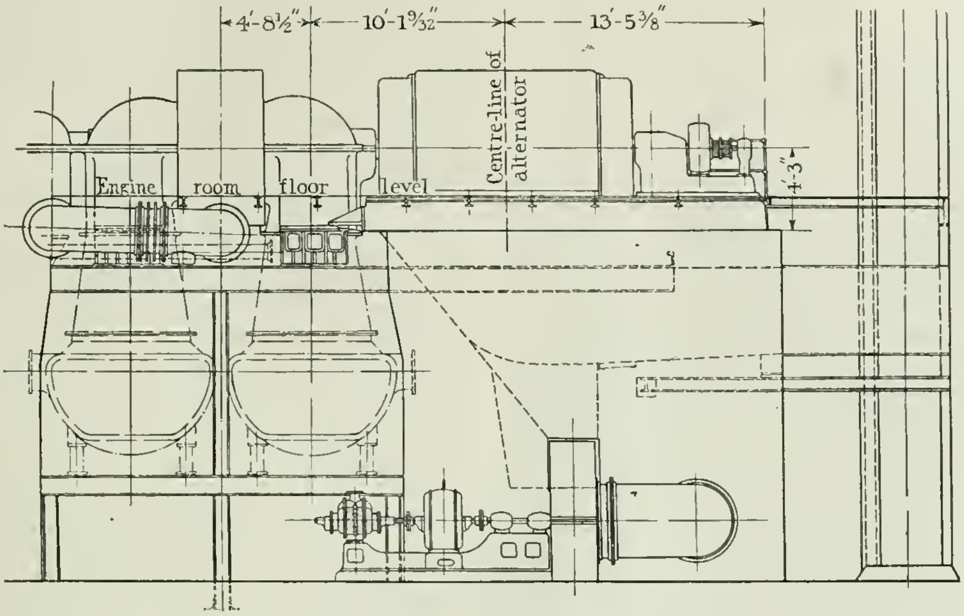


Fig. D.—12 500-kW turbo-alternator, showing ventilating fan coupled to extraction pump motor.

I am pleased that Mr. Taylor agrees with me on the question of the running of the rotors at comparatively low peripheral speed, and that his designs have in some directions run parallel with my own. I notice that in Fig. C he has now adopted my suggestion to fit a second motor.

I agree with Mr. Shaw that great credit is due to both Mr. Bond and Mr. Thompson for the early work done on alternator air coolers. The cooler question was discussed with them, I believe, as early as 1912. So far as the use of inert gases in the closed circuit is concerned, I do not think this is necessary. It is a complication and I think that Mr. Shaw will agree, from his experience of station plant, that it would be somewhat of a nuisance.

I agree with Mr. Shepherd that every effort should be made to improve the mechanical construction of alternators. It is a natural desire on the part of designers that the mechanical construction of high-speed alternators should be improved. Present-day design has proved itself to be a robust construction, and Mr. Shepherd's doubts cast upon the design of conductor have not proved in practice to have any foundation, as the conductors after many years of operation have upon removal been found to be in an excellent state of preservation with the insulation undisturbed. The designs illustrated have withstood the most severe short-circuits, and have proved that both conductors and insulation will withstand " the tremendous hammer-like blows on short-circuits." I realize that the enclosing of the whole of the windings in metal, concrete or similar material, has great attractions, but again Mr. Shepherd must not forget that there are many difficulties which prevent this being done, amongst which the first that occurs to me being the expansion trouble. I do not think that we have been backward in considering the liquid cooling of alternators, as this problem has long been one of many subjects for research by manufacturers.

Mr. Taylor's and Mr. Hill's views upon the question of field-breaking on the whole confirm the conclusions in the paper, but the tests show that with the main field circuit opened suddenly by a simple (quick-break) switch, the alternator voltage falls more rapidly than under any other condition. The increase in the value of the alternator reactance due to the tunnel slot is actually greater than the estimate given by Mr. Hill.

## SCOTTISH CENTRE, AT GLASGOW, 13 FEBRUARY, 1923.

**Mr. C. W. Marshall:** Some figures of alternator failures which have occurred in Glasgow may prove of interest. Out of a total of 21 turbo-alternators installed, 16, or 76 per cent, have failed. Considering machines of modern construction only, the failures allocated to the different firms which have supplied the machines are shown in the following table.

| Firm | Capacity of sets, in kW | No. of sets | No. of failures | Percentage of failures |
|---|---|---|---|---|
| A | 6 000 | 4 | 1 | 25 |
| | 18 750 | 3 | 3 | 100 |
| B | 6 000 | 2 | 1 | 50 |
| | 18·750 | 2 | 0 | 0 |
| C | 6 000 | 2 | 2 | 100 |
| | 3 000 | 1 | 1 | 100 |

Only serious failures are included in the table, and the figures appear to indicate that alternators are very unreliable, but this is, of course, not the case. The troubles which have occurred are due to the following causes: (1) Inability of windings to withstand short-circuits on the external system; (2) slack cores due to flimsy end plates; (3) defective arrangement of out-going leads between alternator and cable-sealing bells; (4) magnetic-circuit failures; and (5) rotor-winding failures. The last-named have all occurred in rotors of the laminated type, and have not been of a very serious nature. I shall be glad if the author will deal with the following questions in his reply. Are the percentages of breakdowns (Fig. 2) based on the total number of alternators installed since 1912? On page 442 the author emphasizes the necessity for examination and testing. What tests are recommended, and how often should they be applied? What increase in efficiency results from the use of tunnel slots? Referring to the integral and separately driven fans mentioned on page 448, can the author give the quantitative figures in regard to these two types? What are the relative costs of the ordinary wet air-filter and closed systems of ventilation? Is the quantity of oxygen in a closed system not sufficient to cause combustion of all the insulation in the machine in case of fire?

**Mr. D. T. Powell:** The author considers that it is advantageous to have a soft wrapping round stator bars instead of insulating them with a hard material, and I recently saw a case in which this preference seemed justified. Several large alternators were built for a 6 600 volt supply and the engineer considered that it might be an advantage to wind the machines for only about 2 500 volts and to put transformers in series with them. In practice this did not prove a good arrangement because the insulation of the stator bars broke down, the very contingency that he was trying to provide against. These stator bars were, of course, carrying a very heavy current, as the machines were of about 8 000 kW capacity, and naturally the copper expanded a great deal. The result was seen when some of the bars were taken out for examination. Not only bars which had broken down were removed, but also some which had not failed. At first sight there appeared to be no defect at all, but when the bar had been cut into sections one could see that the mica inside the outer covering was entirely pulverized, showing the extent of the relative movement between the hard mica tube and the copper. This continued in the machine until finally the insulation broke down at the corners of the mica tubes. There is, I think, no doubt why this insulation failed. The only remedy suggested at the time was to rewind the stator bars and apply harder insulation. I am unable to state whether these re-insulated bars have been more satisfactory. I think that a flexible wrapping would have been better and would have allowed the copper to expand without damaging the insulation. In that connection I would also suggest that the drying-out of alternators may do a considerable amount of harm, especially if carried out, as it is sometimes, with direct current. The current simply heats the winding without heating the core, and then relative movement between the copper and the insulation takes place and very probably causes permanent damage. Other people dry-out by short-circuiting an alternator and running it at something approaching full-load current. This is probably a better method but may also lead to trouble, as the excitation is very small and the heat is largely carried by the copper. In most cases it should be sufficient to run the machine unexcited for a good many hours and allow the windage to start the drying of the machine, and thereafter, if a reasonable insulation resistance be obtained, gradually to excite the machine, taking a considerable number of hours to bring it up to full voltage.

**Mr. F. H. Whysall:** My own experience bears out the evidence given in Fig. 2, which illustrates the very low percentage of failures of Parsons alternator stators in the British Isles during the past 10 years. It appears that all the failure percentages given are less than 1 per cent. In the list of Parsons alternators (Table 1) I note that the largest size actually installed for a speed of 3 000 r.p.m. is 18 750 kVA, and it is gratifying to note that, as the author points out on page 441, in this country we are ahead of America as regards size and speed rating, although quite recently an argument for using units of not more than 10 000 kW capacity was that this size represented the limit for a speed of 3 000 r.p.m. On page 439 the author very properly gives credit to de Laval for developing a satisfactory form of double helical reduction gearing for use with his simple impulse turbine, and I have seen early forms of this in collieries in South Yorkshire doing very heavy work through shafts no thicker than a lead pencil. While there appears to be no real difficulty about gearing in connection with turbine drives in practice, there is no doubt that much trouble has been experienced, in my opinion due more to inexperience or faulty workmanship of engineers responsible than to any other cause. There is no doubt, however, that gearing is a complication which anyone would wish to avoid, if the object could be accomplished by other and better means. Reverting to the question of breakdowns in alternator stator windings, the author does not refer to the valuable help which manufacturers have received in the prevention of serious breakdowns by the use of extremely sensitive and efficient modern systems of protection. Many faults which under previous conditions might have resulted in complete burn-outs, are so quickly dealt with that no serious damage is done, and it is only in an exceptional case that a fault occurs of such a nature as to do serious damage. I am in agreement with the author's views in regard to ventilation. In the case of a continuous stream of fresh air it has been my experience that large quantities of dust accumulate in ventilating ducts, no matter what kind of filter is used. I have also heard of a case where with a wet air-filter the supply of air was completely cut off owing to low-temperature conditions which caused the filter to freeze up and shut off the air supply entirely. I am glad that the author holds the opinion that the introduction of a main-field regulator for exciters is not essential, because I think that no power station engineer was ever in favour of the complication. The author makes no reference to instability of excitation due to the low voltage of the exciter. I refer to the possibility of interruption owing to defective brush contact. I have known the mere contact of an attendant's oily finger on slip-rings or commutator to cause a serious interruption of the field circuit.

**Mr. A. E. McColl**: I am particularly interested in the latter portion of the paper in which the author gives the voltages in the rotor under short-circuit conditions. In 1910 similar trouble was experienced with an alternator in this district. Prof. Miles Walker's paper * on the short-circuiting of alternators pointed the way to a solution. The rotor end-caps when taken off showed signs of arcing and pitting on the portions adjacent to the core. I believe that the actual separation distance was about ½ mm. It was thought that the arcing was probably caused by current surges set up by large reciprocating-engine-driven alternators running in parallel with the turbo-alternator. Tests were made, but the results did not indicate that such was the case. Ultimately, however, the cause of the trouble was traced to external short-circuits to which the alternator had been subjected. The obvious solution, in view of Prof. Miles Walker's paper, was to bond the rotor end-shields rigidly to the core. The author strongly advocates the separately driven fan. With large turbo-alternator installations one is prepared to sacrifice efficiency to a small extent in order to obtain a reliable and secure drive for auxiliary plant. I think it preferable to have a direct-driven fan even at the sacrifice of ½ per cent in efficiency, merely in order to reduce the number of parts which may fail. It is most unsatisfactory to have a large unit temporarily out of commission due to the failure of some small auxiliary part. The author condemns dry-cloth filters and I am sure that we are all in agreement with him on this point. Applied to small machines they are not very satisfactory and in certain locations and under certain atmospheric conditions a cleaning staff in constant attendance is practically necessary. In large machines the dimensions of a dry-cloth filter are so considerable that the arrangement becomes impracticable. The author condemns wet filters on the score that free moisture is apparently carried through. The detection and measuring of this free moisture is not at all a simple matter and I should like the author to give some information on his method of research in this direction. Some time ago I had a number of tests made in order to arrive at a figure for the free moisture, the test procedure being to insert in the incoming air a search coil calibrated for percentage humidity against insulation resistance. If the insulation resistance for a corresponding percentage humidity in the incoming air fell below the calibrated curve, the assumption was made that free moisture was present. It was not possible to say, however, to what extent moisture in excess of natural humidity was present. The water cooling of rotors is advocated, but what is its advantage? Rotor excitation forms a very small proportion of the total loss and if there is any gain it appears to be in the quantity of air used. As this is only a matter of 7 to 8 per cent, the small gain obtained does not seem to justify the additional complications entailed in water cooling. It would be interesting if the author would give his opinion regarding the highest permissible voltage allowable for turbo-alternators. Mr. B. G. Lamme when discussing a paper before the American Institute of Electrical Engineers some time ago laid great stress on the fact that 11 000-volt alternators were successfully running with one phase earthed on single-phase railway service. This, he maintained, was equivalent to a 19 000-volt three-phase alternator running with its neutral point solidly earthed. If the generating pressure can be raised to 19 000 volts three-phase, as Mr. Lamme's statement seems to imply, the range of direct transmission can be increased without the use of transformers. Can the author say if such a proposition is feasible?

**Mr. E. Seddon**: The subject is of special interest to central station engineers, as well as to designers. High-speed alternators with rotors of small diameter entail longer cores and a correspondingly increased length of shaft between the alternator bearings. Such design calls for greater refinement in balancing the rotors dynamically. Up to the critical speed the rotor revolves about the centre of the shaft, and at higher speeds tends to revolve around its own centre of gravity. Information on methods of balancing is lacking. I have obtained good results by placing weights 120° behind the mid-point of the shaft markings. I should like the author to express his views on this point. Until some genius evolves a design for moving a balance weight in the rotor whilst running at high speed the balancing of these machines will remain a laborious operation. The author refers to the overheating of end caps. I have had experience of this trouble where the insulation below the caps was almost totally destroyed, and it was found that the only remedy was to make the caps a thoroughly good fit on the rotor core. I disagree entirely with the author in regard to the question of separately driven fans for supplying cooling air to the alternators. In my opinion we have far too many accessories attached to these large units. It is a very serious matter for a large machine to be put out of service owing to the failure of the fan motor or its wiring. I know of two cases where a turbo set had to be shut down owing to the failure of the fan motor. I think that most central station engineers will agree that it is preferable to make each unit as completely self-contained as possible. The author's explanation of reverse polarity on exciters, and the method proposed for overcoming this difficulty, are of great interest.

---

* *Journal I.E.E.*, 1910, vol. 45, p. 295.

**Mr. M. Pitt:** In order to reduce excessive eddy-current losses in stator slot conductors the author advocates the use of a special standard conductor. While this may occasionally seem necessary, my experience shows that machines likely to be subjected to heavy short-circuits require windings to be as strong as possible. In any but small machines the stator winding can usually be arranged to have 1, 2 or 4 bars per slot, and it is quite possible to design a suitable solid or composite slot conductor in which the eddy-current losses are comparatively low, even on low-voltage machines where the stator current is heavy. It would have added to the value of the paper if the author had given some particulars of his experience with modern fireproof insulated rotors. On large machines the problem of providing even cooling and eliminating hot spots is a difficult one. The stator is less difficult to ventilate than the rotor, especially as the dimensions are not so restricted, and if the stator be cooled properly the cooling of a fireproof rotor is not of special consequence. The limiting factor to the output of large 2-pole machines is then likely to be the magnetic loading—probably the saturation of the rotor core. Mr. Marshall asked for definite figures regarding separate ventilating fans. On a 5 000 kW 3 000 r.p.m. turbo-alternator the friction, windage and fan losses are approximately 100 kW. The actual rotor windage and friction losses are only a small proportion of this, so that if the external fan is considered desirable—and it might be coupled to one of the motor-driven auxiliaries—there is a possible saving of 40 kW, as the efficiency of a high-speed rotor fan is seldom higher than 25 per cent. Eddy currents in the rotor and arcing to the end bells are likely to occur unless special care is taken in fitting the caps and keys to ensure a good metallic contact. The author gives an instance of excessive rotor heating caused by flux pulsations as the result of bad tooth spacing. Load flux waves, especially with good power factors, are distorted and vary considerably. A steady stator M.M.F. wave-form would reduce flux variation and also the rotor heating. Has the author ever experimented with chorded windings, with a view to eliminating the wide variations of the resultant stator M.M.F. wave?

**Mr. A. P. Robertson:** Regarding the air-cooling system, I think that we shall ultimately adopt a closed type. There is a definite amount of oxygen in the air, and in the closed circuit there may not be enough oxygen to burn even the insulation, but if the insulation were burned the copper and other metal parts might be saved. When a burn-out takes place in an alternator, the fanning action of the rotor is similar to that of the fan in a smith's fire, and the rush of oxygen burns up the metal. I am not sure what effect the rush of inert gas would have on the metal, but I should imagine that it would not be so serious as oxygen. I have had some experience of exciter instability. In the ordinary shunt-wound exciter the time-lag between the movement of the rheostat handle and the building up of the voltage is quite appreciable. On page 453 the author mentions that the voltage on the exciter has been built up by means of the rheostat preparatory to synchronizing. Owing to the time-lag the voltage is still building up, and resistance has then to be inserted for the purpose of steadying the voltage. It is very difficult at this juncture to keep the voltage constant. In order to overcome this difficulty it has been a common practice to energize the exciter field by means of a battery. The exciter voltage then responds very quickly to any movement of the rheostat and no trouble has been found due to the variation in voltage of the battery when charging. We have used this method for many years in Glasgow and are still doing so, but there is no doubt that it would be an advantage if an exciter could be produced which would be stable and would also respond quickly to any movement of the rheostat. This would be very much better than having resistance in the main field circuit, and would also eliminate the battery, which is undoubtedly a weak link in the chain.

**Professor G. W. O. Howe:** With reference to the curves shown in Fig. 1, I should like to know why, in plotting the ordinates, the power of the machines has been multiplied by their speed. If the object is to represent the size of the machines, one would expect to find the quotient and not the product. The author has shown oscillograph records of the wave-form of the voltage. I presume that tests were made to ensure that the damping of the oscillograph was correct. It would be interesting to learn whether any attempt was made to detect the presence of the tooth ripple by methods of resonance. Although one feels a certain amount of pride in the success of British electrical engineering firms in making such very large alternators, I do not know whether the policy of installing a small number of these very large units, instead of a large number of small units, is a wise one. I am afraid that those in charge of power stations are rather tempted to emulate one another in putting into their stations a few of these huge machines, thus greatly reducing the real factor of safety of the station. I have grave doubts as to whether the gain in efficiency, in cost or in space, obtained by installing, say, 4 or 5 huge alternators instead of a dozen or more generators of one-half or one-third the size, is sufficient to justify the increased risk of a serious breakdown imperilling the continuity of supply, especially where the whole industrial activity of a large district is dependent upon the electrical supply.

**Mr. W. Ross:** In describing the patented method of cooling an alternator, the author recommends a separate fan for supplying the cooling air, basing his recommendation on the score of economy. To my mind the use of a separate fan is a retrograde step, as it only secures increased economy at the expense of reliability, and in any case the increase in economy must be very small. The majority of engineers will, I think, agree that a self-contained machine of average efficiency is to be preferred. I am interested in the author's description of the closed system of cooling, and should like to have his opinion regarding the use of spray coolers in place of surface coolers, which seem to have some favour in America. The connection of the cooler to the suction side of the pump seems rather dangerous, as, in the event of a tube splitting, the pump might lose the water and serious damage result before this was noticed. The reduction of fire risk seems to me to be very clear, as in addition to the restricted amount of air there are also the products of combustion to dilute the already small quantity of oxygen present. It was stated recently in an American paper, as the result of some tests with $CO_2$ for fire extinction, that air diluted with 10 per cent of $CO_2$ would not support combustion. I should also like to know the author's opinion with regard to the best methods of extinguishing alternator fires.

**Mr. J. Rosen** (*in reply*) : The information given by Mr. Marshall, based upon his experience of alternator breakdowns, is instructive. In Fig. 2 the percentage of breakdowns is based on the total number of rotating-field alternators installed and includes breakdowns on all the early machines as well as the more modern ones. In reply to Mr. Marshall's question on the tests to be applied in the periodic examination of the plant, I would suggest the following :—

> *Preliminary.*—(1) After the plant has been in commission for about two months, the alternator stator end shields should be removed and the stator end windings examined for possible movement due to short-circuits. The winding stud nuts should be tightened. (2) After the first heavy short-circuit on the alternator the stator windings should be examined at the first opportunity.
>
> *General.*—(1) The alternator should be opened out once every 12 months and the stator end shields and rotor removed. The stator core, conductors, and end windings should be examined thoroughly for movement and abrasion of the insulation. The winding stud nuts should be tightened, if necessary. (2) The complete stator windings should be pressure-tested to 50 per cent above working pressure, between phases and to earth for one minute ; the stator windings during this test should be dry. Such an examination should be carried out at the same time as the annual overhaul of the turbine is made.

It is difficult to give the exact improvement in efficiency resulting from the use of the tunnel slot, but this improvement is quite appreciable, as not only is the flux in the air-gap and stator teeth more uniformly distributed, but the pole-face losses are reduced to a minimum. It has, however, been possible to obtain exact figures for the improvement in efficiency when using a separately driven fan. For example, a 5 000 kW alternator requiring 20 000 cub. ft. of air per minute for its ventilation would, if ventilated by fans on the rotor, absorb 90 kW, or 1·8 per cent of the output. From this figure would be deducted 10 kW for the loss due to the windage of the rotor body, leaving 80 kW as the actual loss in the fan. This is a conservative figure and compares with the power of 20 kW absorbed by a motor driving a separate fan. The actual gain by using a motor-driven fan is therefore 1 per cent of the output. This gain remains approximately constant for turbo-alternators up to the largest sizes.

Concerning the relative costs of the wet air-filter and the closed system of ventilation, the air coolers are little or no more expensive than a good design of wet-air filter. The enclosed system of ventilation has the further advantage that there are no long external ducts, so that the total cost in most installations would probably be less than when using the ordinary wet air-filter. The volume of air in the enclosed circuit of a 10 000 kVA alternator is approximately 1 100 cub. ft., containing 20 lb. of oxygen. This quantity of oxygen could consume 7½ lb. of carbon or about 20 lb. of wood, but as the principal product of combustion is carbonic acid gas, and a flame is extinguished when only 4 per cent of carbonic acid gas is present, the amount of wood consumed would only be about 1 lb. The total weight of combustible material in the alternator, including wood packing and insulation, exceeds 400 lb.

Mr. Powell agrees that the flexible insulation is the most satisfactory solution of the stator insulation difficulties. I am aware of the machines to which he refers, and it will probably interest him to know that one of these alternators has been replaced by a Parsons alternator, with the flexible insulation which is now running direct on the 6 600-volt supply in parallel with the existing alternators, coupled through the transformers. It has now been running for two years without difficulties of any kind.

I agree that unless precautions are taken in drying-out alternators under short-circuits, local heating must take place. In my opinion, the best way to dry an alternator on site is to run it below half speed, and to pass the necessary current through the stator windings under short-circuit. By this means, dangerous local heating due to the eddy currents induced under the conditions occurring when the alternator is run short-circuited at full speed is eliminated.

Mr. Whysall refers to difficulties with gearing, and I can assure him that Messrs. Parsons have had no failures of gearing which has been fitted in land installations. I agree that the present forms of alternator protection are a great safeguard and in many cases have prevented a complete burn-out by tripping the machine from the busbars.

I would refer Mr. McColl and Mr. Ross to my reply to Mr. Partridge (see page 466) on the question of alternator ventilation. I would also refer to the reply to Mr. Marshall, from which it will be seen that the improvement in efficiency by using a motor-driven fan is 1 per cent.

In the original tests for free moisture, when air filters were used, air was tapped off and the moisture contents measured by means of the ordinary calcium chloride tubes, but later, in order to obtain a more practical method, moisture detectors were designed, and it is now possible to obtain a check upon the free moisture present in the cooling air, without providing elaborate apparatus. The moisture detector as originally designed consisted of a brass or copper cylinder, around which a sheet of press-spahn 0·2 mm thick was bound with Eureka wire spaced well apart. The insulation resistance of the press-spahn between the Eureka wire and the tube was measured by means of the ordinary testing instruments, such as a "megger." In using this apparatus two similar detectors are employed, one of which is screened by means of a blanket to prevent any free moisture present from impinging on it, and the second one is exposed directly to the cooling air. By taking a series of readings, a direct indication of the condition of the air leaving the filter is obtained. The arrangement is shown diagrammatically in Fig. E and the curves are shown in Figs. F and G with short explanatory notes. Fig. E also gives a diagram of connections for measuring the condition of the insulation by means of a milliammeter, the detector being coupled to the d.c. supply.

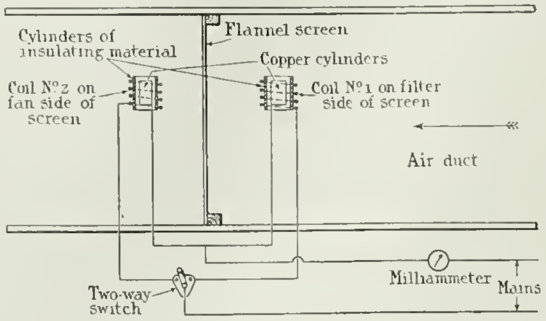

Cylinders of insulating material
Flannel screen
Copper cylinders
Coil N°2 on fan side of screen
Coil N°1 on filter side of screen
Air duct
Milliammeter
Mains
Two-way switch

Fig. E.—Diagram of connections for moisture-detecting apparatus.

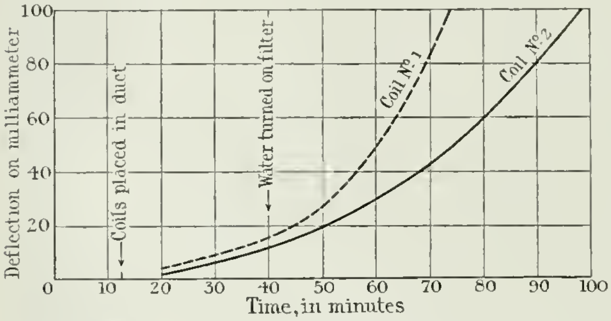


Fig. F.—Moisture-detecting apparatus. Curves showing relation between insulation resistance of two coils.

The insulation resistance of each coil falls at the same rate until the water is turned on the filter, after which the insulation resistance of the coil on the filter side of the screen falls more rapidly. This is due to the presence of free moisture in the duct, which only affects this coil.

I would refer Mr. McColl, on the question of high voltage, to my reply to Mr. Selvey in the London discussion. There are difficulties to be surmounted, but I see no reason why, if engineers desire them, three-phase alternators should not eventually be designed for generating direct at 20 000 volts.

In reply to Mr. Seddon, there are naturally many difficulties in balancing electrical rotors, but I think that the most suitable method is to run the rotors up to speed to enable the windings to take their final positions. I prefer that the rotors should be run up to overspeed while the windings are hot. On the question of separately driven fans, I would refer Mr. Seddon to my replies to previous speakers.

In reply to Mr. Pitt, the modern rotors insulated with the special insulation to withstand high temperatures have proved satisfactory after many years of operation, and no troubles have been experienced due to the qualities of the insulation used. The question of types of stator windings is one for very wide discussion and cannot be dealt with in detail here. Although chorded windings are used, the wave-forms given in the paper were obtained without their use.

In reply to Mr. Robertson, I have had experience of only one fault on an alternator fitted with the enclosed-circuit system of ventilation, and in this case the machine was tripped from the busbars by the operation of the self-balanced protective relays; one conductor only was damaged and the remainder of the windings and insulation were untouched. The balanced protective gear localized the fault and I think the enclosed system of ventilation was instrumental in preventing the burning of the adjacent insulation, owing to the limited quantity of air available for combustion. This question is dealt with fully in my reply to Mr. Marshall. The separate excitation of exciters is not now necessary, as with the use of the series turns on the exciter poles the exciters can be made stable at all voltages required for the operation of the plant.

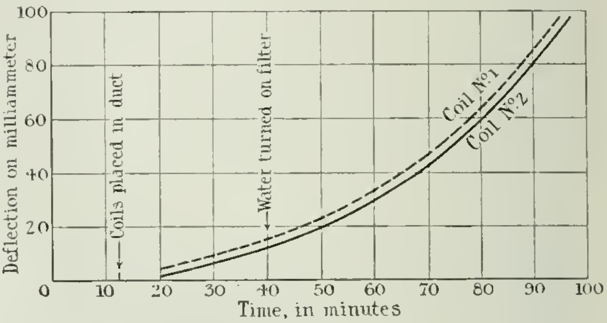


Fig. G.—Moisture-detecting apparatus. Curves showing relation between insulation resistance of two coils.

The insulation resistance of each coil is falling at the same rate, clearly indicating that no free moisture is passing into the air duct.

In reply to Professor Howe, the product of the power of the machines and the speeds has been used in Fig. 1 as it gives a "Factor of Difficulty" in designing and manufacturing such plant. That the wave-forms of E.M.F. of the alternators described in the paper are satisfactory, is confirmed by the fact that in no case has there been disturbance in telephone systems where such alternators are used. It may sometimes be felt that the size of alternators is increasing too rapidly, but it must be remembered that the size of plant is only comparative, that the earlier and smaller machines were designed for the loads then available in one station and that the large units now being considered are very necessary, in order to deal with the very much greater demands for power. Remembering that power stations are now interlinked, there is more available spare plant than in the earlier days; the number of failures of supply due to turbo-alternator breakdowns may be considered negligible.

In reply to Mr. Ross, the only spray-type cooler which I saw in America used for the enclosed system of ventilation had been discarded for the ordinary filtering system. The objections to such coolers are the same as when they are used in the normal way for filtering the air. If a fault is found in a tube of a surface cooler the section of the cooler should be put out of commission and the tube plugged immediately. The precaution of putting the cooler on the suction side of the pump is to prevent water from leaking into the air ducts through small holes only. Several methods have been described for extinguishing fires but I think that the enclosed system of ventilation is the greatest safeguard. I have had steam sprays fitted to alternators, but fortunately it has not been found necessary to use them. Chemical extinguishers should be avoided, as the chemicals harmfully affect the insulation and after their use it is advisable entirely to rewind the alternator. There is also the possibility of further breakdown due to the action of the chemicals upon the varnish.

## North Midland Centre, at Leeds, 20 February, 1923.

**Mr. J. W. J. Townley:** I note that in Table 1 reference is made to a machine of 47 500 kVA; is that a single alternator or is the output obtained from two machines connected to the shafts of a cross-compound turbine? The latter arrangement is, I believe, preferred by the turbine designer for generating sets of that size. The author has dealt with high-speed turbo-alternators, but the turbine designer frequently desires to run his low-pressure end at a somewhat lower speed than the high-pressure turbine, which means two alternators in the case of very large sets, one running at the highest practicable speed and the other connected to the low-pressure turbine at a considerably lower speed. This, of course, greatly simplifies the problem for the alternator designer, and if Messrs. Parsons are now prepared to build single alternators of 47 500 kVA, the 100 000-kVA machine of the cross-compound design is within sight. With reference to these very large machines, some particulars were recently published of a 65 000-kVA turbo-alternator now being constructed in the United States. If the author has any information in regard to this machine (I understand that he has recently returned from America) I should be glad if he would give some details in his reply. The machine is, I believe, designed to run at 1 200 r.p.m. In a recent issue of a German technical journal some particulars were given of the 60 000-kVA turbo-alternators built in that country during the war, and certain particulars were also given of a design for a machine of 160 000 kVA running at 1 000 r.p.m. The rotor diameters were given as 2·25 m for the former, and 2·7 m for the latter. It appears that the peripheral speeds, and therefore the stresses on the rotors, of these and the American machine are very much in excess of anything hitherto contemplated in this country, and I should like to know the author's opinion of these proposals. Reference is made in the paper to the difficulties in obtaining satisfactory cooling in high-speed machines. When water cooling was proposed some years ago and actually carried into effect by Messrs. Parsons, I came to the conclusion that this system of cooling would be universally adopted for large high-speed machines, and I am now somewhat surprised to find the author of opinion that water cooling is unnecessary even for large machines running at 3 000 r.p.m. One can readily understand that in the case of a high-speed machine the relative proportions of iron and air space are considerably modified, the air space requiring a very much greater proportion of the whole, and this naturally results in a somewhat indifferent mechanical construction. The author points out that satisfactory core construction is important in the design of a reliable machine. Is the stator core construction in modern high-speed machines perfectly satisfactory when designed for air cooling? I am disappointed that no reference is made to the maximum temperatures reached in these machines, as I believe that manufacturers have a great deal of data, obtained by the generous use of embedded temperature detectors, as to the hot spots upon their machines, this information not being ordinarily passed on to the user. In an American journal recently some figures relating to the temperatures reached upon the Niagara Falls machines were given, and in one machine the maximum temperature was 390° F. in the stator copper, which appears to be excessive. I do not, of course, suggest that British machines ever reach such temperatures, but I believe that there are hot spots in many machines which reach temperatures very much in excess of anything which thermometers can indicate. I agree that rigid insulation should be avoided, as a certain amount of movement of the stator bars cannot be prevented, and for the effectiveness of the Parsons method of obtaining this flexibility I can vouch, as I have seen some insulation taken off a machine (after being in use for 6 or 7 years) which was then in a very soft flexible condition and would permit a considerable amount of movement of the stator bars without cracking. It may be that with the increasing length of modern alternators the operating engineer should consider more carefully the question of loading his machines and, in order to avoid excessive movement of the stator bars, should load the machine up slowly so that the copper and iron will heat and therefore expand together. The net movement of the stator bars would then be merely the difference between the expansion of the two metals. The total movement, even in the first case, is small, being about ⅛ in. for a stator length of about 8 ft. and 120 degrees F. rise, but it must have an effect upon the insulation if constantly repeated. The author refers to the closed-circuit air filter. I quite agree that this is the best method of dealing with the air-cleansing problem, and it has the additional advantage of mitigating fire risks. He suggests that it is inadvisable to allow water to come into contact with air, but in a design of closed air filter which I have recently seen, the water trickles down a series of plates in the form of a film. The advantage of this type of air filter is that there is no risk from burst tubes, which might have a serious effect. Has the author considered the use of fireproof insulation for end windings? One of the greatest dangers in a modern alternator is a fault occurring at that point, which usually sets fire to, and results in the complete destruction of, the windings. A completely fireproof construction would almost entirely remove this risk. The most valuable part of the paper is, I think, that in which the author gives particulars of his experiments with rotor caps. I feel that we are on the wrong lines in having solid metal caps, as the stresses upon the cylindrical cap are very unequal and tend to distortion. The old system of steel-wire or strip-bands was no doubt unsatisfactory, but this form of construction might be developed and be a more satisfactory solution of the problem than the present solid cap. The author refers to the rather high voltages which can be induced in the shaft and rotor body of high-speed machines. I have experienced this trouble. In order to prevent the circulation of current in the shaft some manufacturers insulate one of the bearing pedestals, but I think it is preferable to short-circuit the shaft inside the alternator bearings. The latter device, of course, involves brushes running upon the shaft at this point. On page 458 the author calls attention to the dangers of open-circuiting the rotor winding with a quick-break switch without discharge resistance, owing to the excessive currents which may flow through the keys, shaft and rotor caps. In a recent paper * it was suggested that to open-circuit these windings by means of a field switch without discharge resistance was a perfectly safe proceeding from the point of view of voltage-rise in the rotor winding itself; but the present author shows that there is another danger which must be borne in mind.

**Mr. G. B. Melton**: From a constructional point of view I am very much interested in the sand-blast action on the conductors. If by digging a hole in the ground near the point of air supply to an alternator it be possible to provide material which will strip the insulation in one minute, I think that we shall have to get rid of both dry and wet air-filters. I am also interested in the pressure set up in the water-cooled rotors. Perhaps the author will state the internal water pressure corresponding to a speed of 300 to 400 ft. per sec. The rotor bonding mentioned is a very satisfactory feature. Reversal of exciter polarity under short-circuit and other abnormal conditions does occur, but I have never found it to be very harmful. The instruments simply work off the scale and their connections have to be reversed. Two machines of which I have intimate knowledge used to reverse at very frequent intervals and no harm was done. The rotor end bells might be constructed similarly to a wire-wound gun, i.e. wound with rectangular-section wire, provided that the ends can be secured. I was rather surprised at the low voltage found by the author in the rotor body under short-circuit, and I should be glad to know whether it was a single-phase or three-phase short-circuit. Instances are known of the breaking down of the insulation under the exciter bearing, and on at least one occasion a machine was actually shut down because an arc was formed between an oil vent pipe and the stator, under single-phase short-circuit conditions. I believe that the existing practice in many American stations, particularly on the Canadian side, is to connect lightning arresters to earth across the rotor and across the exciter bearing pedestal in order to protect the insulation, and I should be glad if the author would deal with this point in his reply.

**Mr. J. F. Mather**: I agree with one or two of the previous speakers that the enclosed system of ventilation for alternators is now obtaining recognition, and that most large machines in the future will be designed with ventilating systems of this type. I also think that the Parsons design of ventilating system is the most scientific and most efficient in use at the present day, but the externally driven fan used is a weak link in the chain. The fan is such a vital piece of the apparatus that a failure of the air supply leads in a very short time to difficulties. I believe that with the Parsons machine, even if running on no load, a failure of the air supply will very soon result in a dangerous rise in the temperature of the rotor and stator if the field magnets are excited. This being so, I should like to suggest to the author a compromise between the inefficient fan mounted direct on the rotor shaft and the fan driven by a separate motor, the idea being to drive the fan by means of worm gears and shafting from the main shaft of the alternator in a similar manner to that in which the governor is driven at the steam end of the machine. There might be some little difficulty in arranging the shafting for the fan, and there would be a fairly considerable amount of power to be transmitted. In the case of a 15 000 kW set, for example, the ventilating fan absorbs about 170 h.p. I think, however, that the scheme would not present any insuperable difficulty, and it would certainly have much to recommend it from the point of view of reliability. It will probably be mentioned that such a design would entail an increase in the length of the machine, and with Parsons machines this is a very important point. A comparison between Parsons machines and those of equal output of other types will show that the former are usually somewhat the longer. From the point of view of calculation of steam consumption of the set this method of driving the fan would not be under any disadvantage, because it is usually specified that in calculating the consumption the power delivered from the alternator terminals shall be reduced by the power required for ventilating the stator and the exciter of the machine.* The question of reactance is also distantly connected with the ventilation of the machine. At first sight there may not appear to be any connection between these two things, but I speak now from the point of view of the general lay-out of the plant. When external reactances are to be used, a very convenient place for housing them is the space in the foundations directly beneath the alternator. With the enclosed system of ventilation this space will be required for the air ducts and cooler, and the reactances will necessarily be placed elsewhere. The problem with which central station engineers are faced to-day is very often to fit a comparatively large-sized machine into an engine room that is very much too small for it, an engine room that was perhaps designed many years ago for plant of an entirely different type. It is not therefore always an easy matter to find a place for the reactances and at the same time to make a suitable arrangement of the main cables. From this point of view it appears to be desirable that all the reactance should be contained in the machine itself. I believe that external reactances when installed provide about 30 or 40 per cent of the total reactance in circuit. With the tunnel type of slot which the author recommends for other reasons, it should not be very difficult to include in the machine windings as much reactance as required.

---

* J. A. Kuyser: "Protective Apparatus for Turbo-Generators," *Journal I.E.E.*, 1922, vol. 60, p. 761.

* With the gear-driven fan this power would be deducted automatically.

**Mr. S. D. Jones :** Would it not be possible to design an air cooler similar in nature to an evaporative condenser ? The air would be circulated through the cooler tubes and the circulating water would drip over the outside of these tubes. A steady stream of air could be directed against the water to carry off the vapour through air ducts to the outside of the building. This would involve an additional fan for the outside air circulation, and possibly the cooler to do the work would take up too much space. The cooler tubes would always remain clean inside, as only clean air circulates in them, and they could be designed to give the greatest possible cooling surface between the inside air and the trickling water outside.

**Mr. S. E. Fedden :** The author's remarks regarding the advantages of the Parsons stator winding are justified in practice, and the possibility of withdrawing a faulty bar with little or no disturbance to its neighbours is fully appreciated by those in charge of the operation of turbo-alternator plant. Our experiences with wet-air filters as applied to high-tension alternators confirm from many points of view the great desirability of the closed air system. Water-cooled rotors constitute a doubtful expedient, as apart from danger of possible leaks on to the E.H.T. stator winding there is danger of the circulation stopping without warning owing to the passages becoming choked. The author directs attention to the danger of breaking down field windings through the too rapid interruption of current. As " kicking " coils are now out of date and as the old and well-tried shunt break is not the latest practice, what is to be done ? Perhaps a liquid starter converted to act as an " interrupter " might meet the case. With reference to the loss of field of shunt exciters on light load, as we were amongst the first to recommend the trial of a few turns of series winding on the Parsons exciters we can confirm this as a remedy. The design and general insulation of rotor slip-rings are not referred to ; the steel rings should be not less than 2 in. broad, and a little more creeping surface should be allowed on the mica forming the foundation. The connection from rotor winding to slip-ring is often a source of trouble. The Parsons design has proved very successful owing to the attention given to these details. The author does not direct attention to the importance of main-terminal design on alternators. Possibly Messrs. Parsons have not experienced trouble in this respect. Their terminal connectors consist of broad laminated copper strip flexibly insulated and yet rigidly clamped between broad slabs of insulating material carried by gunmetal brackets. There being no porcelains to be broken by main cable movement, this terminal has proved most successful.

**Mr. D. M. Buist :** On the whole I agree with the author's remarks upon the subject of insulation, but as an additional security from the user's point of view I would stipulate that all coils on both stator and rotor, and especially the end turns, after being wound should be subjected to a temperature and pressure greater than will probably be encountered in operation. I am glad to note that the author's firm seems to have paid particular attention to the question of cooling the end turns, as this is practically the only portion of the windings where the cool air can be brought into direct contact with the source of the heat. Referring to the question of eddy currents in rotors, I am glad to see that the author devotes to it the attention that it deserves. I have encountered at least two breakdowns which could only be attributed to the eddy currents induced in the rotor caps. The first of these substantiates the author's opinion that to insulate the cap from the rotor is not a satisfactory remedy. This was the method adopted in the case to which I refer, and distortion of the cap, combined with mechanical weakness of the insulation, resulted in heavy sparking between the cap and the body each time the rotor circuit was opened. The second breakdown occurred on a larger machine of different make, and in this instance a piece of the cap weighing nearly ¾ lb. broke off and tore up the stator windings. When this happened the machine was on low load, and so in this case it is probable that centrifugal force completed what the sparking had commenced. In view of the above, therefore, I heartily endorse the author's recommendation that quick-break switches without discharge resistances should be employed to break the main-field circuit only in an emergency.

**Mr. G. P. Henzell :** I should like to make a few remarks with reference to ventilation. Most of us will agree that both the wet and dry types of air filter are, generally speaking, unsatisfactory in practice. I think that the closed system of ventilation is undoubtedly the right thing. I recently saw an alternator having a capacity of, I think, 10 000 kW, that had just been opened out after 12 months' running on the closed ventilating system ; there was not even a speck of dust to be seen on the windings. I am not at all in favour of the separate fan, however, as it is an additional auxiliary. The author is probably correct in saying that we cannot design such an efficient fan to run on the rotor shaft, but I think that we can design a fan sufficiently strong mechanically. Even though it is less efficient, I think it is better than the separate fan with all the attendant risks of breakdown. I have never been able to get to the bottom of the question of alternator temperatures, as no one seems to have definite views as to what the limit is. The majority of operating engineers are strongly inclined to keep on the safe side. Personally, I think that the factor determining the safe limit is, to a great extent, expansion, and not the temperature that the insulating material will withstand. I have had breakdowns on alternators, and in most cases examination showed that the conductors had moved inside the insulation, which then flaked or powdered off. I should like to endorse the remarks of a previous speaker on fireproof end-winding. I think this is a most important point; most serious damage is caused by end-winding fires.

**Mr. J. Rosen** (*in reply*): In reply to Mr. Towlney, 47 500 kVA is the output of one alternator of the 50 000 kW unit, which has a total kVA capacity of 64 500. This unit is now being manufactured by Messrs. Parsons for the Crawford Avenue station of the Commonwealth Edison Company, Chicago. Where the load is available, it is not unreasonable to use 100 00-kW units with cross-compound turbines, and I am confident that such units will be installed during the next few years. The 47 500 kVA alternator mentioned above will run at 1 800 r.p.m. Mr. Townley asks if the figure of 2·7 m at 1 000 r.p.m. is safe. I think that this peripheral speed of 464 ft. per sec. is the maximum at which rotors should be run with the information at present available. Personally, I prefer not to exceed a peripheral speed of 400 ft. per sec.

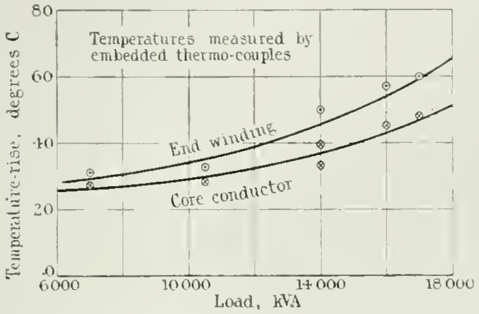


Fig. H.—Curves showing temperature-rise of end-windings and core conductors in an 18 000-kVA alternator.

In reply to Mr. Townley and Mr. Melton, research in the direction of steel-wire and steel-strip bands for supporting the rotor end-windings has been carried out, but a metal cylinder of some form must be used on which to bind the wire; otherwise, the wire has to be applied directly to the rotor windings. Alternator rotors have been fitted with caps filled with binding wire, owing to the difficulty in obtaining suitable high-tensile bronze, and have run quite satisfactorily. With the lower peripheral speeds, however, the complication of binding wire is not necessary. There are difficulties which prevent stators being entirely water cooled, and I have dealt with this question in reply to Mr. Shepherd (see page 467). The stator core in the present methods of construction and supports has proved to be very reliable.

I agree with Mr. Townley's figures on the movement between stator conductors and the core, but the flexible insulation has overcome these troubles. On the whole, I think that we do not run to such high temperatures in this country as in the plants manufactured in America. I attach a typical curve (Fig. H) of conductor temperatures in an 18 000 kVA alternator, as measured by embedded thermo-couples. With present materials it is impracticable to obtain a completely fireproof construction of stator winding, but with the enclosed system of ventilation the damage has been limited to the point of breakdown only; it has been proved that the damage does not extend to other parts, owing to the comparatively small quantity of air present. I find that the insulated pedestal is more satisfactory than the use of short-circuiting brushes.

I have had some experience of the coolers with water trickling down the plates, but this arrangement is similar to the eliminators in the ordinary wet air-filter; the water appears to collect at the edge of the plates and is blown over in the form of large drops.

In reply to Mr. Melton, the pressure in the tubes exerted by the water at 300 ft. per sec. is about $2\frac{3}{4}$ tons per sq. in. In regard to the voltage induced in the rotor shaft, this was under a three-phase short-circuit. I would remind Mr. Melton that even this pressure of 30 volts would circulate a very heavy current of some thousands of amperes through the rotor body. I have heard of the practice of connecting lightning arresters between one of the rotor terminals and earth, but I did not see in America an installation to which such a device was fitted. Although in this country their use was considered some years ago, I do not think that they have been adopted.

Mr. Mather proposes to use a fan geared in some way to the alternator shaft. I would refer him and also Mr. Henzell to Fig. D on page 467, in which is shown an arrangement used on a 10 000 kW machine for driving the fan from a pump motor. The greater number of Parson alternators are run without external reactances, but if reactances are proposed I have no doubt at all that provision could be made to incorporate them in the foundation lay-out with the enclosed system of ventilation. Naturally, their position must be considered before the foundation plans are settled.

It has been found that sufficient cooling surface can only be obtained by the use of "gilled" tubes, and that the rate of heat transmission from the air to the water is low and is the limiting factor in the design. The evaporative principle offers no advantage in this respect, and in addition entails, as pointed out by Mr. Jones, an additional fan and ducts. There is, therefore, not sufficient to be gained by the use of the evaporative principle to offset the additional cost.

I am very pleased to hear that Mr. Fedden's views coincide on the whole with my own. I do not think that in the normal operation of the plant it is necessary to utilize the special liquid "interrupter," as it is only necessary to open the main field in emergency or when the alternator excitation has been reduced; this can then be done by means of the ordinary quick-break switch.

Mr. Buist is correct in assuming that both the stator and rotor windings should be subjected to pressures greater than that which would be encountered in operation.

I agree with Mr. Henzell as to the difficulties due to expansion and to movement of the conductors. The helically stranded conductors with flexible insulation illustrated in Fig. 8 have replaced conductors of several alternators in which the laminated conductors with hard insulation were previously used.

# THE USE OF SINGLE-CORE SHEATHED CABLES FOR ALTERNATING CURRENTS.*

By Professor W. CRAMP, D.Sc., Member, and NORA I. CALDERWOOD, M.A., B.Sc.

(*Paper first received 2nd September*, 1922, *and in final form 8th January*, 1923.)

## SUMMARY.

It is frequently a matter of convenience to use single-core lead-covered cables for transmitting power by means of alternating current, and in such cases the magnitude of the loss arising from the eddy currents induced in the lead sheath becomes a matter of importance. Recently some power-supply authorities have refused to connect to their lines any distributing system depending upon the use of such cables.

The eddy losses in the sheaths of these cables may be divided into two groups, called herein "sheath eddies," and "sheath circuit eddies." The latter occur only when one or more cables have their sheaths connected at more than one place.

The losses are analysed for a single cable, a pair of single-phase cables, and a set of three-phase cables.

It is shown that the sheath eddies are in all cases negligible, and that the sheath circuit eddies may be kept within reasonable limits by proper regulations regarding the spacing of the cables.

It is suggested that the I.E.E. Wiring Rules should contain such regulations, and that so long as these are adhered to there is no justification for refusing to connect single-core lead-covered cables to any ordinary a.c. system. The necessary data are given for the framing of the regulations.

Similar questions arise regarding armoured cables. The results in this case are awaiting the conclusion of the experiments now being carried on at the University of Birmingham.

The adoption of alternating currents for small and large distributing systems has resulted in an ever-increasing use of cables provided with a protecting metal sheath, from which it follows that the effect of eddy currents in the sheath is of importance, especially in Great Britain, where underground lines are more common than in America or on the Continent.

The subject is also a matter of moment in many large works and collieries, especially in those cases where a change has been made from an old d.c. supply to a new a.c. system, in which it is desired to use as many of the existing cables as possible.

Again, paper-insulated cables admit of large currents for a given section of copper and a given temperature-rise, and the use of paper entails the use of a protecting waterproof sheath which is usually made of lead.

It is not always convenient to adopt a multi-core cable for an a.c. system. There are many instances where, on account of special circumstances, such as the run to be negotiated or the presence of existing cables, it is economical or convenient to adopt cables of the single-core type. In the course of practice extending over many years, one of the authors has never hesitated to use long lengths of single-core lead-covered cable on a.c. circuits, and has never had the least trouble due to heating of the sheath. Notwithstanding this experience, it now appears that some power-supply authorities are objecting to single-core a.c. cables, and even refuse to connect them to their mains. The reason for this action apparently is that these authorities fear the heating effect of eddy currents in the sheath which are induced by the current in the core of the cable itself and by neighbouring circuits.

Current textbooks contain little but vague statements as to the magnitude of such heating effects, though several recent American papers deal with other aspects of the problem. It therefore seemed desirable to calculate and put on record the relative magnitude of this loss as compared with that due to the normal resistance of the core itself. The justification for this comparison lies in the fact that the heat due to the copper core as well as that due to the eddy currents in the sheath must ultimately be dissipated by the surface of the sheath. If then we express both in the form of watts/cm$^2$ of the sheath surface we shall have a measure of the increased temperature-rise of the cable due to the sheath eddy currents.

The eddy currents in the sheaths of a pair of cables laid side by side, each carrying a known alternating current, may be divided into two main groups:—

(A) Eddy currents whose outward and return paths lie entirely in the sheath of one cable, called hereinafter "sheath eddies."

(B) Eddy currents whose outward path is along one cable, and return path along another, called hereinafter "sheath circuit eddies."

It will be manifest that the latter can never exist if each sheath is entirely insulated from every other, or if there is no metallic connection at more than one point of a pair of cable sheaths. Thus, if bonding, or switchgear wiped joints exist at only one end of a system, all currents of class (B) will disappear. But the currents of class (A) cannot be avoided altogether by any means short of a non-metallic sheath, which, if it could be devised, would eliminate not only these but many other troubles. We are of opinion that cable makers would do well to direct their attention to this suggestion, for so long as metal sheaths are used and wiring rules, particularly colliery wiring rules, are what they are, bonding at both ends of a circuit is usually a matter of necessity.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

If we can show that eddy currents of class (A) are negligible in magnitude, then power-supply authorities will be well advised not to irritate consumers by refusing to connect single-core cables to their systems, but to adopt such rules as will keep the heating losses due to (B) within safe limits.

To prove the former and to give data for the latter is our object in the following analysis, and we begin with currents of class (A). As a general case of common occurrence and one in which these eddy losses will be at their worst, we may consider a single-phase circuit consisting of a pair of lead-covered cables lying side by side along a straight run. We assume the mean radius of sheath to be $r$ cm, the centres of the pair of cables to be $l$ cm apart and the thickness of the sheath to be $S$ cm. Since $S$ is small compared with either $r$ or $l$, the magnetic field at any point P in the sheath may be considered to be uniform throughout the thickness at that point. The distance $l$ must always be greater than $2r$, so that the fraction $r/l = K$ cannot be greater than $0 \cdot 5$.

Referring to Fig. 1, and assuming that the cable whose centre is at A carries a current $\hat{I} \sin 2\pi ft$ amperes away from the observer, for which the cable whose centre is at B forms the return circuit, then at the point P on the mean circumference of the lead sheath the magnetic field due to the current at A is always normal to the radius AP and clockwise in direction. Similarly, the magnetic field at P due to the current at B is always normal to BP and counter-clockwise in direction.

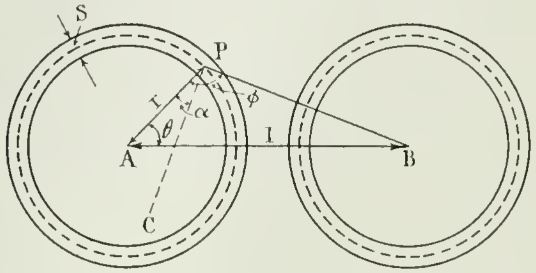


Fig. 1.

This second field may be resolved into two components, (1) along PA and (2) at right angles thereto. The circumferential field through P around A is therefore the sum of two components, while the field normal to the sheath is due to the current in B only. We thus have two series of eddy currents, the first due to the sum of the circumferential fields and tending to flow in radial planes, and the second due to the normal fields and tending to flow in tangential planes. If $\theta$ is the angle PAB, and $\alpha$ the angle APC (where PC is perpendicular to PB), the circumferential magnetic density at P is

$$B_1 = \frac{0 \cdot 2\hat{I} \sin 2\pi ft}{r}\left(1 - \frac{r^2 - rl\cos\theta}{r^2 + l^2 - 2rl\cos\theta}\right)$$

$$= \frac{0 \cdot 2\hat{I} \sin 2\pi ft}{r}\left(\frac{1 - K\cos\theta}{1 + K^2 - 2K\cos\theta}\right)$$

On the above assumptions, if the cable has a length $L$ cm, then through a zone of the sheath of radial thickness $y$ (from the mean circumference) and length $L$ the magnetic flux is

$$\phi_1 = \frac{0 \cdot 2\hat{I} \sin 2\pi ft}{r}\left(\frac{1 - K\cos\theta}{1 + K^2 - 2K\cos\theta}\right)Ly$$

which will produce along an element of the boundary of the zone an E.M.F.

$$\delta E = -\frac{d\phi_1}{dt}$$

$$= \frac{-0 \cdot 4\pi f\hat{I}\cos 2\pi ft}{10^8 r}\left(\frac{1 - K\cos\theta}{1 + K^2 - 2K\cos\theta}\right)Ly \text{ volts}$$

Since the length of the cable is great compared with its circumference, the resistance of the element of the boundary is

$$R = \frac{\rho L}{r d\theta dy}$$

where $\rho$ is the specific resistance of the material of the sheath.

The eddy current along the element is

$$di = -\frac{1}{R}\cdot\frac{d\phi_1}{dt} = -\frac{0 \cdot 4\pi f\hat{I}\,[\cos 2\pi ft]\,(1 - K\cos\theta)}{10^8\rho(1 + K^2 - 2K\cos\theta)}y d\theta dy$$

The power lost in the element is

$$\delta E di$$

$$= \frac{0 \cdot 16\pi^2 f^2\hat{I}^2\cos^2(2\pi ft)}{10^{16} r\rho}\cdot\frac{(1 - K\cos\theta)^2 Ly^2}{(1 + K^2 - 2K\cos\theta)^2}d\theta dy \text{ watts}$$

The power lost in each element of thickness $S$ and width $rd\theta$ is

$$\frac{0 \cdot 04\pi^2 f^2\hat{I}^2\cos^2(2\pi ft)LS^3}{3 \times 10^{16} r\rho}\cdot\frac{(1 - K\cos\theta)^2}{(1 + K^2 - 2K\cos\theta)^2}d\theta$$

If $I$ be the R.M.S. value of the current, the mean power lost is

$$dP = \frac{4\pi^2 f^2 I^2 LS^3}{3 \times 10^{18} r\rho}\cdot\frac{(1 - K\cos\theta)^2}{(1 + K^2 - 2K\cos\theta)^2}d\theta \text{ watts}$$

Therefore the power lost in the whole sheath due to the cicumferential fields is $\int_0^{2\pi} dP$ and entails the integration of the expression

$$[(1 - K\cos\theta)^2/(1 + K^2 - 2K\cos\theta)^2]d\theta$$

This may be written

$$\int_0^{2\pi}\left\{\frac{1}{4} + \frac{1}{4}\frac{(1 - K^2)^2}{(1 + K^2 - 2K\cos\theta)^2} + \frac{1}{2}\cdot\frac{1 - K^2}{1 + K^2 - 2K\cos\theta}\right\}d\theta$$

The second and third of these three integrals are not found in ordinary textbooks and their solution is therefore given in some detail in Appendix I, from which on substituting the limits we find:—

$$\int_0^{2\pi} dP = \frac{4\pi^2 f^2 I^2 LS^3}{3 \times 10^{18} r\rho}\cdot\frac{\pi(2 - K^2)}{1 - K^2}$$

and the watts/cm$^2$ of the mean circumference of the lead sheath due to this cause become

$$\frac{2\pi^2 f^2 I^2 S^3 (2-K^2)}{3\times 10^{18} r^2 \rho (1-K^2)} \quad . \quad . \quad . \quad . \quad (a)$$

It will be seen from this expression that as the cables are spaced further and further apart the value of $K$ becomes less and less, so that ultimately the fraction $(2-K^2)/(1-K^2) = 2$; and then the eddy loss in the sheath is that usually calculated for one long, straight, independent cable. Under these circumstances also, expression ($a$) becomes $4\pi^2 f^2 I^2 S^3/(3r^2\rho \times 10^{18})$. This divided by $S$ gives the watts lost per cm$^3$ of the lead sheath. For metal sheets this loss is generally given in terms of the maximum magnetic induction $B$. Upon substituting in the above expression the obvious relationship $I^2 = r^2 B^2/0\cdot 08$ we find that the eddy loss in watts/cm$^3$ is $\pi^2 f^2 B^2 S^2/(\rho \times 6 \times 10^{18})$, which is the ordinary formula for the eddy loss in thin sheets.* Thus the proximity of the second cable has the effect of increasing this loss in the ratio $(2-K^2)/(2-2K^2)$.

Our calculation has proceeded thus far on the assumption that in each element of the sheath the distribution of the flux is substantially uniform throughout its thickness. This, as Sir J. J. Thomson has pointed out,† is true only if the product $\pi S\sqrt{(\mu f)}/\sqrt{\rho}$ is small. Now for lead $\mu = 1$, $S = 0\cdot 25$ (about), and $\rho = 20\,000$ C.G.S. units (about). Thus in Thomson's sense this product is always small, for with a frequency of 50 it is of the order $0\cdot 04$; whence we conclude that for a lead sheath our assumption is justifiable.

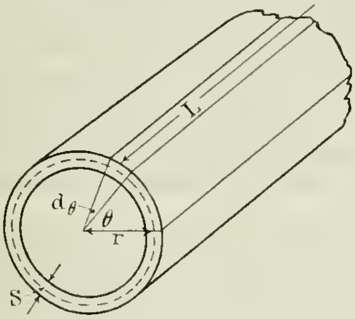


FIG. 2.

*Radial field.*—Similarly, considering the normal component of the field in the sheath of cable A due to the current in cable B, we have (see Figs. 1 and 2)

$$B_2 = \frac{0\cdot 2\hat{I}\sin(2\pi ft)\,.\,l\sin\theta}{r^2+l^2-2rl\cos\theta} \quad . \quad . \quad . \quad . \quad (b)$$

The flux through an element of length $L$ and width $rd\theta$ is

$$d\phi_2 = \frac{0\cdot 2\hat{I}\sin(2\pi ft)\,.\,KL\sin\theta d\theta}{1+K^2-2K\cos\theta}$$

and the flux through an area $Lr\theta$ of the cable sheath is

$$\phi_2 = \frac{L\hat{I}\sin(2\pi ft)}{10}\Big[\log(1+K^2-2K\cos\theta)\Big]_0^\theta$$

when $\theta$ is measured from the neutral line AB (Fig. 1).

The distribution of this radial field about the cable is a matter of considerable interest. In Fig. 3 the sheaths of two cables having centres at A and B are indicated by the full and the dotted circles respectively. The full curve about A having two lobes indicates the distribution of radial flux about the cable A due to the current in B. The figure is so drawn that all radial lengths such as CD indicate flux densities along those radii. The lower lobe is really of opposite sign to the upper, but this is not indicated in the figure. The flux density is a maximum at a point on the circumference depending upon the ratio $K$, and the exact value of $\theta$ for this maximum is ascertained by differentiating expression ($b$) and equating to zero. We thus find :—

$B_{2max.}$ occurs when $\cos\theta = 2K/(K^2+1)$

For the conditions illustrated in Fig. 3 the angle $\theta$ at which maximum flux density occurs is 36° 52′ from the horizontal, the lead sheaths being then in contact. As they are separated further and further, $K$ becomes smaller and smaller and the angle gradually becomes greater until $K = 0$, when the cables are at an infinite distance apart and $\theta = \pi/2$. It is clear from this figure that the lines at C and E running along the cable are, as it were, the core centre-lines of the flux lobes, and will stand in a similar relationship as regards eddy currents set circulating in the sheath by variation of this flux; whereby it is also seen that these same lobes might represent to some suitable scale the magnetomotive forces due to the circulating currents. In this manner they illustrate and enforce a principle which is of importance to us and is expressible as follows :—

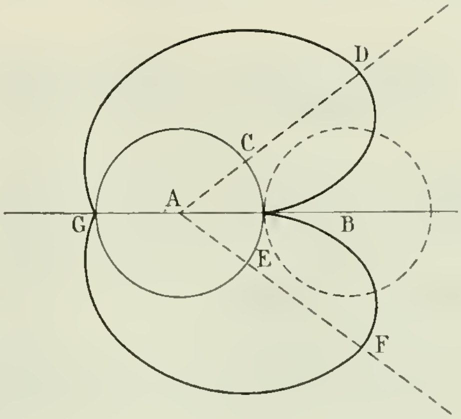


FIG. 3.

> If a magnetic field oscillate through a uniform conducting sheet, the eddy currents excited thereby will so distribute themselves as to tend to produce a magnetomotive force distributed in a manner similar to the exciting flux.

From this principle we infer that the eddy-current bands will run lengthwise along the sheath and be zero at C; also that they will be distributed in bands of opposite sign on either side of C and of E, so that between C and E about AB all the current is of one sign return-

---

* Cf. *Journal I.E.E.*, vol. 33, p. 951; also STEINMETZ: "Alternating Current Phenomena," 3rd edn., chap. 11.

† See *Electrician*, 8 April, 1892, p. 599.

ing along the segment between E and C on the side remote from AB.

The flux through a circuit made up of two elementary longitudinal strips of the sheath lying in radial planes displaced by angles $\theta$ and $(\pi - \theta)$, respectively, from the plane AB is

$$\frac{L\hat{I}\sin(2\pi ft)}{10}\Big[\log(1 + K^2 - 2K\cos\theta)\Big]_{\theta}^{(\pi-\theta)}$$

$$= \frac{L\hat{I}\sin(2\pi ft)}{10}\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}$$

The E.M.F. acting around the elementary circuit is

$$\delta E = \frac{-2\pi fL\hat{I}\cos(2\pi ft)}{10^9}\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}$$

Neglecting the resistance of the end paths, the section of an element of the circuit is $Srd\theta$, and its length $2L$, so that the resistance of the elementary circuit is $2\rho L/Srd\theta$.

Therefore

$$di = \frac{-2\pi fL\hat{I}\cos(2\pi ft)Sr}{2\rho L10^9}\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}d\theta$$

And

$$dP = \frac{2\pi^2f^2L\hat{I}^2\cos^2(2\pi ft)Sr}{10^{18}\rho}\left\{\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}\right\}^2 d\theta$$

Then the power loss due to this cause in the upper semi-cylinder of the sheath is

$$P = \frac{2\pi^2f^2L\hat{I}^2\cos^2(2\pi ft)Sr}{10^{18}\rho}\int_0^{\pi/2}\left\{\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}\right\}^2 d\theta$$

This expression when averaged over one period and divided by $\pi rL$ gives the loss in watts/cm² as

$$\frac{2\pi f^2I^2S}{10^{18}\rho}\int_0^{\pi/2}\left\{\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}\right\}^2 d\theta$$

We have not succeeded in obtaining a general solution of this integral, and in consequence we have been compelled to evaluate it for each particular case by a method of numerical integration. The formula adopted and our reasons for choosing it are given in Appendix II, in which is included also a portion of a table of one set of the values calculated.

The power losses as thus deduced are somewhat greater than can ever occur in practice, since we have neglected the effect of the reaction of the eddy currents upon the exciting field, as well as the resistance of the cable ends and the self-induction of the eddy-current circuit. They are therefore to be regarded as limiting values; and if we can show that in all ordinary sizes of cable the total effect as calculated is inappreciable, it follows a fortiori that the cables will be safe in all cases so far as this loss is concerned. In order to arrive at the worst possible case, we remark that the presence of a second cable enhances the loss due to the circumferential field by the multiplier $(2 - K^2)/(1 - K^2)$, i.e. the loss increases as the cables approach one another, up to the limit when their sheaths are in contact. Similarly, examination of the expression for the radial field shows that this also increases up to the same limit—thus the eddy currents are worst when the cable sheaths actually touch.

As regards the question of the relative phase of the currents in the two cables, it is evident that if there is any phase displacement other than $\pi$ (which is the case just considered), the resultant field in either sheath for a given current is less than the case where there is no phase displacement. The case of 3-core cables is outside the scope of the present inquiry, and has been dealt with elsewhere.* From these considerations we conclude that the worst case for the eddy currents that we are considering occurs when a pair of single-phase, single-core sheathed cables are laid side by side with their sheaths in contact, and for this reason we select for $K$, for integrating purposes, the value $\frac{1}{2}$.

With regard to the question of size, it will be evident that the greater the size of the core and the smaller the diameter of the sheath, the greater will be the loss; thus low-tension cables are in a much worse position than high-tension cables, and if the losses in the former are small those in the latter will be negligible.

For our table of values we therefore select standard 660-volt paper-insulated cables with standard thicknesses of dielectric and lead sheathing, and taking the six largest of these we calculate the following losses:—

(1) Core copper loss, assuming the maximum current allowable by the I.E.E. Wiring Rules.

(2) Loss due to eddy currents produced by the circumferential field in the case of a pair of cables laid side by side with their sheaths in contact.

(3) Loss due to eddy currents produced by the radial field under the same conditions as (2) above.

Each of the above is then divided by the mean cylindrical surface of the lead covering, giving us the watts/cm² which the lead must dissipate in the form of heat produced by each of the three causes; from which it is immediately apparent that the loss due to the circumferential field is in every case entirely negligible. In the last column of Table 1 the loss due to eddy currents is shown as a percentage of the core loss. This figure is the most valuable as it shows by how much the power which the lead has to dissipate is increased by the use of such single-core cables.

In the formulæ as developed it will be noted that all dimensions are in centimetres, but for the convenience of English and American cable makers the values in the table are in the usual English units. The standard English frequency of 50 has been adopted, but for any other frequency the losses may be easily deduced from those given in the table if it is remembered that the loss is proportional to $f^2$.

---

* *Journal I.E.E., loc. cit.*

We think that we are justified in drawing the following conclusions from this table :—

(1) The eddy-current losses in the lead sheaths of standard cables due to causes under (A) (page 477) are so small that they cannot even in the worst case materially affect the temperature-rise of the cables.

(2) Standard cables appear to be so proportioned and rated that the copper loss per $cm^2$ of the sheath surface is about constant. This is to be expected since the currents in col. 2 have been arrived at by the Institution on the basis of a standard temperature-rise, and the whole of the heat has to pass through the surface of the lead sheath.

(3) Of the sheath losses so far considered, those due to the radial field are far greater than those due to the circumferential field. This fact may be of importance when armoured cables are considered.

TABLE 1.

*Sheath Eddy-current Losses in a Pair of Lead-sheathed Single-phase Cables. Sheaths in Contact.*

($\rho$ for copper $= 1\cdot78/10^6$ per cm cube ; $\rho$ for lead $= 20\cdot8 \times 10^{-6}$ per cm cube ; frequency = 50.)

| Nominal core area | Maximum permissible current (I.E.E.) | Thickness of lead | Mean radius of lead sheath | Copper loss* | Loss due to circumferential field | Loss due to radial field | Ratio : $\frac{\text{Sheath loss}}{\text{Copper loss}}$, per cent |
|---|---|---|---|---|---|---|---|
| sq. in. | amps. | in. | in. | watt/cm² | watt/cm² | watt/cm² | |
| 1·00 | 932 | 0·110 | 0·8345 | 0·018 | $7\cdot8 \times 10^{-6}$ | $579\cdot5 \times 10^{-6}$ | 3·3 |
| 0·75 | 738 | 0·100 | 0·7265 | 0·01729 | $4\cdot8 \times 10^{-6}$ | $330\cdot5 \times 10^{-6}$ | 1·97 |
| 0·60 | 624 | 0·100 | 0·6615 | 0·01696 | $4\cdot2 \times 10^{-6}$ | $236\cdot2 \times 10^{-6}$ | 1·44 |
| 0·50 | 540 | 0·090 | 0·6085 | 0·01658 | $2\cdot7 \times 10^{-6}$ | $159\cdot2 \times 10^{-6}$ | 0·99 |
| 0·40 | 464 | 0·090 | 0·5635 | 0·01651 | $2\cdot3 \times 10^{-6}$ | $117\cdot5 \times 10^{-6}$ | 0·74 |
| 0·30 | 385 | 0·080 | 0·4905 | 0·01743 | $1\cdot5 \times 10^{-6}$ | $71\cdot94 \times 10^{-6}$ | 0·43 |

* Per $cm^2$ of mean sheath surface.

(4) The percentages given in col. 8, though small, are larger than could occur in practice, since the self-induction of the elementary circuits has been neglected (see page 480).

(5) There is no object in considering any cables smaller than those given in the table.

(6) When the value of $K$ is $< \frac{1}{2}$, the loss decreases rapidly and need not be further considered.

We pass next to a consideration of the eddy currents under (B) (page 477), on the assumption that single-core cables are again used but that they are now spaced apart and have a heavy metal connection at both ends, so that each pair forms a closed circuit enclosing an alternating flux. There are only two cases of any importance that are likely to occur in practice, viz. when two single-phase cables are laid side by side, and when the three cables of a three-phase system are laid side by side with the distance between either outside cable and the middle equal to one-half the distance between the outside cables.

(1) CASE OF A PAIR OF SINGLE-PHASE CABLES.

Here again we take $r$ as the mean radius of the sheath, and $l$ as the distance between the cable centres, $K$ being the ratio $r/l$.

Then, referring to Fig. 4, the total flux between the sheaths due to the current $\hat{I} \sin(2\pi ft)$ in one cable and $-\hat{I} \sin(2\pi ft)$ in the other, is

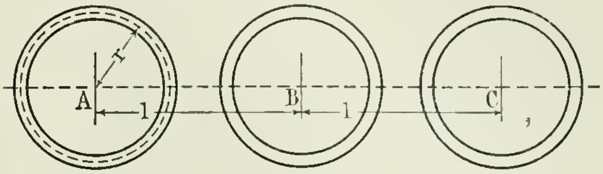


FIG. 4.

$$\phi = 0\cdot92\hat{I} \sin(2\pi ft) \log_{10} \frac{1-K}{K} \text{ (per cm length)}$$

so that the E.M.F. acting around the circuit composed of the two cable sheaths and their bonding is

$$E = -\frac{1\cdot84\pi f\hat{I} \cos(2\pi ft)}{10^8} \log_{10}\frac{1-K}{K} \text{ (per cm run)}$$

The corresponding resistance, neglecting that of the bonding, is $\rho/\pi rS$. Thus the mean loss per $cm^2$ of mean sheath surface is

$$\rho = \frac{3\cdot386\pi^2 f^2 I^2 S}{4\rho\,.\,10^{16}}\left(\log_{10}\frac{1-K}{K}\right)^2 \text{ watts}$$

$$= SI^2\left(\log_{10}\frac{1-K}{K}\right)^2 \times 10^{-7} \text{ watts (nearly) for 50 periods per second.}$$

This is on the assumption that any flux due to one cable *cutting* the other sheath will add nothing to the circulating current, on account of the eddy currents which it will induce in the sheath of that cable. This, although only partially true, is sufficiently near, as will presently be seen.

In Table 2 we have taken the six sizes of cable given in Table 1 and calculated the above loss for five values of $K$ in each size. We have also given the ratio of this sheath loss to the copper loss as a percentage, and the actual distance in inches between the centres of the cables, corresponding to each value of $K$.

TABLE 2.

*Circuit Eddy Losses in a Pair of Standard Single-phase Lead-sheathed Cables.*

($\rho$ for copper $= 1{\cdot}78 \times 10^{-6}$ per cm cube; $\rho$ for lead $= 20{\cdot}8 \times 10^{-6}$ per cm cube; $f = 50$.)

| Nominal area | $K$ | Eddy-current loss | Ratio: $\frac{\text{Sheath loss}}{\text{Copper loss}}$, per cent | Actual distance, centre to centre |
|---|---|---|---|---|
| sq. in. | | watt/cm² | | in. |
| 1 | 0·01 | 0·0966 | 537 | 83·4 |
| | 0·1 | 0·022 | 123 | 8·34 |
| | 0·2 | 0·0088 | 49 | 4·17 |
| | 0·3 | 0·0028 | 16 | 2·78 |
| | 0·4 | 0·00075 | 4·2 | 2·08 |
| 0·75 | 0·01 | 0·055 | 318 | 72·6 |
| | 0·1 | 0·0126 | 73 | 7·26 |
| | 0·2 | 0·005 | 29 | 3·63 |
| | 0·3 | 0·0019 | 11 | 2·42 |
| | 0·4 | 0·00043 | 2·5 | 1·81 |
| 0·6 | 0·01 | 0·039 | 232 | 66·0 |
| | 0·1 | 0·009 | 53 | 6·6 |
| | 0·2 | 0·0036 | 21 | 3·3 |
| | 0·3 | 0·00133 | 7·8 | 2·2 |
| | 0·4 | 0·000306 | 1·8 | 1·65 |
| 0·5 | 0·01 | 0·0265 | 160 | 61·0 |
| | 0·1 | 0·006 | 36·6 | 6·1 |
| | 0·2 | 0·0024 | 14·6 | 3·05 |
| | 0·3 | 0·0009 | 5·4 | 2·03 |
| | 0·4 | 0·00021 | 1·2 | 1·52 |
| 0·4 | 0·01 | 0·0196 | 105 | 56·4 |
| | 0·1 | 0·0045 | 27 | 5·64 |
| | 0·2 | 0·0018 | 11 | 2·82 |
| | 0·3 | 0·00066 | 4 | 1·88 |
| | 0·4 | 0·00015 | 1 | 1·41 |
| 0·3 | 0·01 | 0·012 | 68·8 | 49·0 |
| | 0·1 | 0·0027 | 16 | 4·9 |
| | 0·2 | 0·0011 | 6·3 | 2·45 |
| | 0·3 | 0·0004 | 2·3 | 1·63 |
| | 0·4 | 0·00009 | 0·54 | 1·22 |

It is manifest from this table that we have here to deal with a loss which may produce a dangerous heating effect.

We shall postpone the general conclusions derived from this analysis until we have examined the case of three-phase systems, to which we now turn.

### (2) CASE OF THREE THREE-PHASE CABLES IN ONE PLANE.

We confine ourselves to this case, because when single-core cables are used it is usually under circumstances where this arrangement is by far the easiest to adopt. Also it may be remarked that the only other likely case is that in which the three cables are arranged with their centres at the points of an equilateral triangle, when the eddy losses do not essentially differ from those in the single-phase case already examined. We therefore suppose that the three cables are arranged as shown in Fig. 4, and $K$, $l$ and $r$ have the same values as heretofore. The flux between the sheaths of A and B (Fig. 4) will be produced by the currents in A and B, plus so much of the flux due to C as lies between these two sheaths; and this sum, oscillating at a frequency $f$, will produce an E.M.F. around the circuit composed of A and B and their bonding. In this case, as in the previous one, we suppose that the flux linked with only part of the sheath is producing eddies in the sheath as already calculated, so that no difference of potential exists between A and B on account of it. This is not strictly accurate, but it is quite within the limits of the errors inherent in the calculation.

The E.M.F. arrived at in this way, when squared and divided by the resistance of the two sheaths in series, gives the watts lost due to this cause, but there will be a further loss in cable A due to a similar current flowing along it and returning via cable C. This will be produced by the E.M.F. due to the flux common to A and C. If B did not exist, there would be no difficulty in calculating the value of the current; but its presence renders the result somewhat doubtful. Proceeding, however, on the same assumption as before, viz. that partial linkages do not contribute to the current with which we are now dealing, we may estimate the losses in either A or C. The loss in B is in any case smaller, having the same value as for a single-phase cable carrying a like current, so that the limiting safe distance at which the cables can be spaced is determined by the losses in the outers.

Taking then the currents in A, B and C to be $\hat{I}\sin(2\pi ft)$, $\hat{I}\sin(2\pi ft + 2\pi/3)$ and $\hat{I}\sin(2\pi ft + 4\pi/3)$, respectively, we find that the mean power lost in either A or C due to the current flowing between either and B is

$$\frac{4\pi^2 f^2 \hat{I}^2 S}{2\pi\rho\,.\,10^{18}}\int_0^{2\pi}\left\{\cos\theta' + \cos\left(\theta' - \frac{\pi}{3}\right)\log\frac{1-K}{K}\right.$$
$$\left. + \cos\left(\theta' + \frac{\pi}{3}\right)\log\frac{2-K}{1+K}\right\}^2 d\theta'$$

where $\theta' = 2\pi ft$.

Writing the R.M.S. value of the current in either of the three cables as $I$, we have:—

Mean power lost per cm² of mean sheath surface due to this current

$$= \frac{4\pi^2 f^2 I^2 S}{\rho\,.\,10^{18}}\left\{3\left(\log\frac{1-K}{K}\right)^2 + \left(\log\frac{2-K}{1+K}\right)^2\right\}$$

Similarly the mean power lost per cm$^2$ due to the current common to A and C is

$$\frac{6\pi^2 f^2 I^2 S}{10^{18}\rho}\left\{\log\frac{(1-K)(2-K)}{K(1+K)}\right\}^2$$

The total mean loss per cm$^2$ in either outer is therefore

$$\frac{4\pi^2 f^2 I^2 S}{10^{18}\rho}\left\{3\left(\log\frac{1-K}{K}\right)^2+\left(\log\frac{2-K}{1+K}\right)^2 + 1\cdot5\left(\log\frac{(1-K)(2-K)}{K(1+K)}\right)^2\right\}$$

Now the loss in the middle cable may be written :—

$$\frac{16\pi^2 f^2 I^2 S}{10^{18}\rho}\left\{\log\frac{1-K}{K}\right\}^2$$

and by taking a series of values for $K$ we may compare the losses in either of the outers with that in the cable B. This has been done in the following table, from which it will be seen that the ratio of the two is nearly constant, and may for all practical purposes be taken as 1·4.

TABLE 3.

*Ratio of Losses (Outer/Middle) for a Three-phase Cable.*

| $K$ | Ratio |
|---|---|
| 0·4 | 1·44 |
| 0·3 | 1·42 |
| 0·2 | 1·37 |
| 0·1 | 1·34 |

These values hold, whatever be the material of the sheath.

## GENERAL CONCLUSIONS FOR LEAD-SHEATHED CABLES.

The formulæ developed in this paper are general as regards the material of the sheath, since the specific resistance occurs as a general value, but when applying the expressions to find safe limits for any particular case the corresponding value of $\rho$ must be inserted, as has been done in Tables 1 and 2, and in the summary on page 481. We may now draw the following conclusions :—

(1) In all single-core cables sheath eddies exist. The loss due to them is greatest when the sheaths are closest together, and diminishes as the distance between neighbouring cables is increased.

(2) In the largest low-tension cables made, the sheath eddy loss never exceeds 4 per cent of the copper loss in the core, and consequently is of little importance as a heating effect.

(3) No sheath loss except that due to sheath eddies can exist unless the sheaths are connected at more than one point by conducting material.

(4) With modern switchgear it is not usually possible to avoid connecting at more than one place.

(5) From the point of view of temperature-rise, the question of the length of the run has nothing to do with the advisability of using single-core cables, since so long as they are parallel the loss is proportional to the length, as is also the cooling surface.

(6) The sheath circuit eddy loss is a far more serious matter than the sheath eddy loss. It is greatest in the outer cables of a parallel three-phase main, and has in that case a value approximately 1·4 times as great as in the case of a single-phase main carrying the same current.

(7) Assuming that it is not desirable that the sum of the sheath and sheath-circuit losses should exceed 10 per cent of the copper loss in the cable, then in laying such cables either metallic connection at more than one place between the sheaths must be avoided, or the distance from centre to centre of standard cables as compared with the mean diameter of the lead sheath should not exceed the following limits :—

| Nominal core area | Safe distance, centre to centre | |
|---|---|---|
| | Single-phase | Three-phase |
| sq. in. | in. | in. |
| 1·0 | 2·2 | 2·0 |
| 0·75 | 2·2 | 2·0 |
| 0·6 | 2·2 | 2·0 |
| 0·5 | 2·3 | 2·1 |
| 0·4 | 2·6 | 2·25 |
| 0·3 | 3·1 | 2·6 |

These are the most important sizes, and all the figures refer to standard low-tension lead-sheathed paper cables. For smaller areas the safe distance rapidly increases, but for any special case the safe distance can easily be calculated from the formulæ given. It will be noted that in all cases, except the three largest, the allowable spacing falls within the dimensions of standard porcelain cleats in racks, so that the following recommendation may also be added :—

(8) For all cases, both high and low tension, it is safe to use standard porcelain cleat racks for single-core lead-sheathed cables, provided that the core area does not exceed 0·5 sq. in.

It should be noticed that the cases specifically considered in the paper are the worst that can occur in practice, our object being to discover safe limits rather than to tabulate exact losses. In the case of high-tension cables, for example, where the mean radius of the sheath is so much larger as compared with the core diameter, there is no likelihood of serious heating due to sheath losses, unless the spacing of the cables is quite unreasonably large. We should regard 3 inches to 3½ inches as being perfectly safe for all ordinary cases.

On the other hand, to reduce dielectric stresses it is now not unusual to construct high-tension cables with a jute core. In this case the ratio [(mean radius of sheath)/(core diameter)] is reduced again, but so also is the current-carrying capacity of the core. On the whole these two effects leave the general conclusions at which we have arrived unchanged, but special cases must be specially treated. This matter has been fully considered elsewhere,* as well as the sheath circuit eddies produced in a three-phase single-core-cable system with symmetrical spacing.

The chief sources of error in our calculations are those due to neglect of (*a*) bonding resistances, and (*b*) self-induction. The former is indeterminate, dependent upon circumstances, and reducible by care to a negligible quantity. The latter is by no means negligible, and its values have been calculated in the paper already quoted. Its effect is always to reduce the sheath circuit eddy, and thus provide a margin to the limits we have assigned. This margin, however, becomes of practical importance only in high-tension cables where the dielectric thickness is considerable.

There is one other matter for precaution to which we should direct attention. If to avoid sheath circuit eddies the sheaths are not bonded, a considerable E.M.F. may exist between a pair of sheaths, which in the case of high-tension cables may be really dangerous both to the cables and to those handling them. This voltage is easily calculated from the formulæ already given, and its magnitude as well as various methods of earthing to avoid its effects without actually closing the sheath circuit have been discussed by Clark and Shanklin in the paper already referred to. It will be noted that the analysis always points to the desirability of laying the cables as close to one another as possible. Nevertheless, we do not recommend placing them with their sheaths in contact. We think that the best plan is to cover the lead with a serving of jute, tape or braid, in which case the cables may lie in actual contact. Without this precaution it is possible that at the points where lead actually touches lead, pitting may occur and ultimately lead to a breakdown of the sheath. Therefore, if such a serving be not adopted, the cables should be definitely spaced by cleats.

### ARMOURED CABLES.

We have not yet considered any case in which the sheath is of magnetic material, for the simple reason that such sheaths almost always take the form of wire or tape armouring. The determination of the resistance to eddy currents of such a sheath is almost impossible except by means of experiment, and a series of tests has been instituted at the Birmingham University to discover the limits in such cases and to supplement the work of Whitehead and Fisher.† These will be published later. In the meantime it seems reasonable to ask, as a result of this investigation, that supply undertakings should withdraw the embargo that in some cases has been laid upon the use of single-core cables for low-tension a.c. systems, and substitute therefor a permission subject to the limitations here set forth. We further think that such limitations might well receive the attention of the I.E.E. Wiring Rules Committee, with a view to including them in the Wiring Rules; and we wish to thank Mr. Julius Frith, a member of that Committee, for drawing our attention to this matter and for suggesting the investigation.

## APPENDIX I.

*Case* (*a*).— $\int_0^{2\pi} \frac{d\theta}{(1 + K^2 - 2K\cos\theta)^2}$. [$(1 + K^2)$ being positive and $-(2K)$ numerically less than $(1 + K^2)$, and $K$ being not greater than 0·5.]

Substitute $$\cos y = \frac{(1 + K^2)\cos\theta - 2K}{1 + K^2 - 2K\cos\theta} \quad . \quad . \quad . \quad (1)$$

Then $$-\sin y dy = \frac{-\sin\theta(1 - K^2)^2 d\theta}{(1 + K^2 - 2K\cos\theta)^2} \quad . \quad . \quad . \quad (2)$$

Also $\cos y(1 + K^2 - 2K\cos\theta) = (1 + K^2)\cos\theta - 2K$.

Therefore $$\sin\theta = \frac{(1 - K^2)\sin y}{1 + K^2 + 2K\cos y} \quad . \quad . \quad . \quad (3)$$

From (1), as $\theta$ varies from 0 to $2\pi$, $y$ varies also from 0 to $2\pi$, whence

$$\int_0^{2\pi} \frac{d\theta}{(1 + K^2 - 2K\cos\theta)^2}$$
$$= \int_0^{2\pi} \frac{-\sin y dy(1 + K^2 - 2K\cos\theta)^2}{-\sin\theta(1 - K^2)^2(1 + K^2 - 2K\cos\theta)^2} \quad . \quad (4)$$

Substituting for $d\theta$ from (2), and for $\sin\theta$ from (3), we have

$$(4) = \int_0^{2\pi} \frac{1}{(1 - K^2)^3}(1 + K^2 + 2K\cos y)dy$$
$$= \frac{1}{(1 - K^2)^3}\Big[(1 + K^2)y + 2K\sin y\Big]_0^{2\pi}$$
$$= \frac{2\pi(1 + K^2)}{(1 - K^2)^3}$$

*Case* (*b*).— $$\int_0^{2\pi} \frac{1 - K^2}{1 + K^2 - 2K\cos\theta} d\theta$$

See Todhunter's "Integral Calculus" (1880), p. 278.

## APPENDIX II.

Method of evaluating the expression

$$\int_0^{\pi/2} \left\{\log \frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}\right\}^2 d\theta$$

The value of this integral was obtained by a method derived from Newton's interpolation formula.

---

* *Journal of the American Institute of Electrical Engineers*, 1919, vol. 38, pt. 1, p. 917.

† *Journal of the American Institute of Electrical Engineers*, 1909, vol. 28, pt. 2, pp. 737 and 747.

The general expression is

$$\frac{1}{w}\int_a^{a+rw} f(x)dx = \tfrac{1}{2}f_0 + f_1 + f_2 + \ . \ . \ . \ + f_{r-1} + \tfrac{1}{2}f_r$$
$$- \tfrac{1}{12}(\delta f_{r-\frac{1}{2}} - \delta f_{\frac{1}{2}})$$
$$- \tfrac{1}{24}(\delta^2 f_{r-1} + \delta^2 f_1)$$
$$- \tfrac{19}{720}(\delta^3 f_{r-\frac{3}{2}} - \delta^3 f_{\frac{3}{2}})$$
$$. \quad . \quad . \quad . \quad . \quad . \quad .$$
$$- \text{etc.}$$

Here $f_{-3}$, $f_{-2}$, $f_{-1}$, $f_0$, $f_1$, $f_2$, $f_3$, . . ., are the successive calculated values of the function $f(x)$ corresponding to definite constant increments $w$ of the variable $x$. Also

$$\delta f_{-\frac{1}{2}} = f_0 - f_1,$$
$$\delta f_{\frac{1}{2}} = f_1 - f_0, \text{ and similarly}$$
$$\delta^2 f_1 = \delta f_{\frac{3}{2}} - \delta f_{\frac{1}{2}}, \text{ etc.}$$

The most convenient way of arriving at the integral is to tabulate the successive values of the function and the successive differences in a series of parallel vertical columns, from which the required values are ascertained and then inserted in the formula, in accordance with the general expression. The order of differences up to which the calculation is carried must of course depend entirely upon the rapidity with which the differences decrease as their order increases, and the process is useless unless the series converges. It is assumed that the function and its differential coefficients up to the order of differences employed are continuous, which in the present case is obviously true.

It will be seen that the value of the integral can by these means be obtained to any desired degree of accuracy, which is our reason for preferring it to any of the simpler and more ordinary methods, such as Simpson's or Weddle's rule.

In the case under consideration, the values of the function were calculated for every 10° increase in $\theta$, giving 10 values in all for $f_0$, $f_1$, $f_2$, $f_3$, etc., so that $w = \pi/18$ radians. The differences were taken as far as the ninth order, the final differences being of the order of 1/125 of the value of $f_0$. It will be seen, therefore, that the convergence is sufficiently rapid for the accuracy required. Since $K$ is taken as 0·5 the integral required is

$$\int^{\pi/2}\left\{\log\frac{1\cdot 25 + \cos\theta}{1\cdot 25 - \cos\theta}\right\}^2 d\theta$$

and the following table is a small portion of the actual calculation, inserted here to illustrate the method of setting out the values. The figures are logarithms to the base 10.

| $\theta$ | $f(\theta)$ | $\Delta$ | $\Delta^2$ | $\Delta^3$ | $\Delta^4$ |
|---|---|---|---|---|---|
| 0° | 0·91056 | | | | |
| | | − 0·05366 | | | |
| 10° | 0·85690 | | − 0·08314 | | |
| | | − 0·13680 | | 0·04925 | |
| 20° | 0·72010 | | − 0·03389 | | − 0·01008 |
| | | − 0·17069 | | 0·03917 | |
| 30° | 0·54941 | | 0·00528 | | |
| | | − 0·16541 | | | |
| 40° | 0·38400 | | | | |
| | | | etc. | | etc. |
| | | etc. | | etc. | |

Completing the table in this way and substituting the values derived from it in the formula, together with their appropriate coefficients, the final value of the integral was found to be 3·16385, from which the values in col. 7 of Table 1 in the paper have been calculated.

# DIRECTIONS FOR THE STUDY OF PRESSBOARD FOR ELECTRICAL INSULATING PURPOSES.

(Report Received from the British Electrical and Allied Industries Research Association.)

Contents.

Page
I. Definitions and Terminology .. .. .. 486
  (a) Definition of Pressboard .. .. .. 486
  (b) Terminology .. .. .. .. 486
  (c) Classification of Pressboard .. .. 486
II. Tests—
  Clause 1—Conditioning of Specimens for Test 486
  Clause 2—Tensile Strength and Extension .. 486
  Clause 3—Compression Strength .. .. 486
  Clause 4—Shearing or Tearing Strength .. 488
  Clause 5—Cohesion between Layers (Splitting Test) .. .. .. .. .. .. 488
  Clause 6—Flexibility (Bending Test) .. 488
  Clause 7—Electric Strength .. .. .. 489
  Clause 8—Shrinkage and Swelling .. .. 492
  Clause 9—Freedom from Chemical Reaction 492
  Clause 10—Freedom from Conducting Particles and Pinholes .. .. .. .. 492
  Clause 11—Freedom from Superficial Defects 493
  Clause 12—Effect of Oil .. .. .. 493
  Clause 13—Water Absorption .. .. 493
  Clause 14—Determination of Thickness .. 493
  Clause 15—Determination of Density .. 493
III. Appendix—
  Method of Ascertaining the Electric Strength of Pressboard when Subjected to Long Application of A.C. Stress.. .. .. 494

## I. DEFINITIONS AND TERMINOLOGY.

### (a) *Definition of Pressboard.*

The term " Pressboard " denotes all materials marketed as Pressboard, Presspahn, or Fullerboard, which materials are made by a paper-making process from vegetable fibres, but differ from papers in that they are made on a " Board " machine, and are afterwards subjected to great pressure in order to remove excess of water and to " close up " the sheet, thus producing a solid board. The boards are afterwards dried, and, if specified, are glazed by calendering and planishing.

Note.—Strawboard is not included, as its use is considered undesirable for electrical work.

### (b) *Terminology.*

(i) The term " Longitudinal " denotes the direction parallel to that in which the material travelled during manufacture.

(ii) The term " Transverse " denotes the direction at right angles to that described in (i) above.

(iii) The term " Perpendicular " denotes the direction at right angles to the thickness of the material.

Note.—When the material is built up of superposed layers having the " grain " at right angles, there is no definite longitudinal or transverse direction.

### (c) *Classification of Pressboard.*

Three classes of Pressboard are recognized, as follows :—

*Class A.*—Hard, non-porous, untreated pressboard, having a density exceeding 1·15 after 18 hours' drying at 80° C., and characterized by a relatively high electric strength.

*Class B.*—Soft, untreated pressboard having a density less than 1·15, but not lower than 0·90, after 18 hours' drying at 80° C., and consequently having a relatively lower electric strength combined with greater absorption than Class A pressboard.

*Class C.*—Pressboard impregnated during manufacture with varnish, oil, wax, and the like, or otherwise treated to improve its electrical properties.

## II. TESTS.

### (1) Conditioning of Specimens for Test.

Before the tests specified in Clauses 2, 3, 4, 5, 13, 14, and 15 are carried out, the specimen shall be dried at a temperature from 75° C. to 80° C. for 18 to 24 hours, and the test shall be conducted as soon as the temperature of the specimen has fallen to 20° C. (± 5° C.).

### (2) Tensile Strength and Extension.

The specimen shall be conditioned in accordance with Clause 1 before the tests for tensile strength and extension are carried out.

The form and dimensions of the specimen for test shall be as shown in Fig. 1. The thickness of the specimen shall be the thickness of the material.

The specimen shall be tested to ascertain the ultimate tensile strength and extension on a three-inch gauge length.

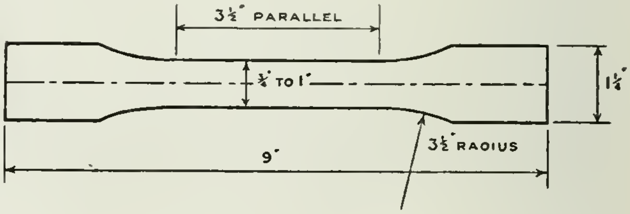


Fig. 1.—Specimen for Tensile Strength and Extension Tests.

The load shall be increased steadily at such a rate that the specimen breaks in about two minutes from the time of the application of the load.

The ultimate tensile strength shall be expressed in lb. per sq. in. (kg per cm$^2$). The extension shall be expressed as a percentage on the original gauge length.

### (3) Compression Strength.

The specimen shall be conditioned in accordance with Clause 1 before the compression strength test is carried out.

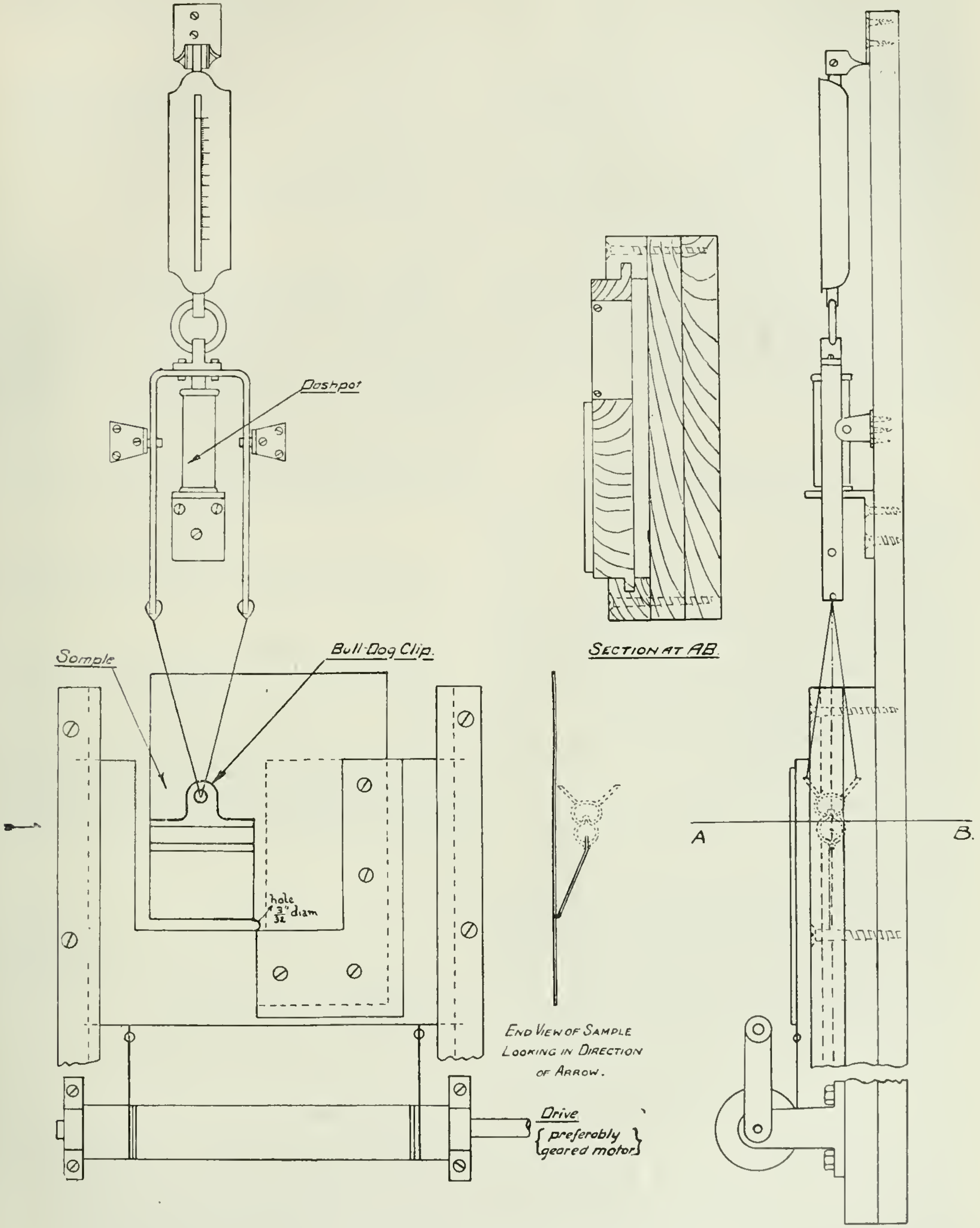

Dashpot
Sample
Bull-Dog Clip.
hole 3/32" diam
Section at AB.
A
B.
End View of Sample Looking in Direction of Arrow.
Drive
{preferably geared motor}

FIG. 2.—Apparatus for measuring the Tearing Strength.

The form of the specimen for test shall be either a cylinder 1 inch long and 3 inches diameter, or a prism 1 inch long and 3 inches square, the specimen being built up with sufficient layers of the material.

The compression faces of the testing machine shall be 2 inches diameter.

The specimen shall be set up for testing so that its centre line is co-axial with the centres of the compression faces of the testing machine.

The layers of the material shall be bedded together by the application of an initial load of 100 lb. per sq. in., and the first measurement of the length of the specimen shall be taken under this load, which shall be included in the load registered in each case.

A series of tests shall then be carried out by the application of increasing loads, in steps of 1 500 lb. per sq. in., each of which shall be maintained for one minute ; and the yield of the specimen shall be measured at the end of each period. The tests shall be continued until the specimen has yielded 25 per cent of its original length when measured as stated above, or the load has reached about 6 tons per sq. in.

### (4) Shearing or Tearing Strength.

The specimen shall be conditioned in accordance with Clause 1 before the test for shearing or tearing strength is carried out.

(*a*) *Shearing Strength.*

Materials above 1/32 inch (0·8 mm) thick up to and including $\frac{1}{8}$ inch (3·2 mm) thick shall be tested to ascertain the pressure required to punch a hole $\frac{1}{2}$ inch diameter.

The load shall be applied steadily, and shall be increased at a rate of about 100 lb. per minute for each 1/32 inch thickness of the specimen.

The clearance between the punch and the die shall be negligible, as obtained by trimming the punch with the die.

The pressure required to punch the hole shall be expressed in lb. per sq. in. (kg per cm$^2$).

Materials above $\frac{1}{8}$ inch (3·2 mm) thick shall be tested as follows :—

A specimen, the dimensions of which shall be 5 inches (127 mm) long, and $2\frac{1}{2}$ inches (64 mm) wide, shall be clamped in a shear testing machine so that both ends of the specimen are sheared off simultaneously. The pressure required to produce shear shall be computed on the total area of the sections sheared, and shall be expressed in lb. per sq. in. (kg per cm$^2$).

(*b*) *Tearing Strength.*

Materials up to and including 1/32 inch (0·8 mm) thick shall be tested for tearing strength as follows :—

The form and dimensions of the specimen for test shall be 6 inches square.

The tearing strength shall be the load required to tear the specimen commencing from a hole 3/32 inch (2·4 mm) diameter punched out of the specimen. The position of the hole and the application of the load shall be as shown in Fig. 2.

Three longitudinal and three transverse tear tests shall be carried out on each material under test. The maximum, mean and minimum values shall be stated.

The load required to tear the specimen shall be expressed in lb. (grammes).

### (5) Cohesion between Layers (Splitting Test).

The specimen shall be conditioned in accordance with Clause 1 before the test for cohesion between layers is carried out.

Cohesion between layers shall be tested by one of the following methods :—

(*a*) A specimen shall be cut to the following dimensions :—

Width = 1 inch.
Thickness = Thickness of the material.
Length = Four times the thickness plus $\frac{1}{2}$ inch.

The specimen shall be supported on V supports spaced apart at a distance equal to four times the thickness of the material under test. A load shall be applied centrally on the specimen and increased until failure occurs. The load required to produce failure and the nature of the fracture shall be stated.

(*b*) A specimen 2 inches square shall be tested to ascertain whether it is possible to split the material parallel to the laminations, when a split has been started at one corner by the insertion of a knife.

### (6) Flexibility (Bending Test).

Flexibility Tests shall be carried out on the material as follows :—

(*a*) *Cold* (*before Baking*).

Each specimen of every thickness up to and including 0·020 inch shall be bent longitudinally and transversely flat on itself, and the effect at the bend shall be stated.

Each specimen of every thickness above 0·020 inch shall be bent longitudinally and transversely through an angle of 90°, and the effect at the bend shall be stated. The diameter of the pin round which the specimen is bent shall be in accordance with the appropriate value given in Table 1 below :—

Table 1.

| Limits of Thickness of Specimen, inch | Diameter of Pin, inch |
|---|---|
| Above 0·020 up to and including 1/32 .. | $\frac{1}{4}$ |
| Above 1/32 up to and including 1/16 .. | $\frac{3}{8}$ |
| Above 1/16 up to and including $\frac{1}{8}$ .. .. | $\frac{1}{2}$ |

(*b*) *After Baking.*

The specimen shall be heated at a temperature from 105° C. to 110° C. for 48 hours, and shall then be bent longitudinally and transversely through 90°, and the effect at the bend shall be stated. The diameter of the pin round which the specimen is bent shall be in accordance with the appropriate value given in Table 2 below.

TABLE 2.

| Limits of Thickness of Specimen, inch | Diameter of Pin, inch |
|---|---|
| Up to and including 0·010 .. | $\frac{1}{8}$ |
| Above 0·010 to 0·020 .. | $\frac{3}{16}$ |
| Above 0·020 to 1/32 .. | $\frac{3}{4}$ |
| Above 1/32 to 1/16 .. .. | $1\frac{1}{4}$ |
| Above 1/16 to $\frac{1}{8}$ .. .. | 2 |

(*c*) *After Heating in Oil.*

The specimen shall be heated in transformer oil, complying with British Standard Specification No. 148 for light grade oil, at a temperature from 115° C. to 120° C. for 48 hours, and shall then be bent longitudinally and transversely through 90°. The diameter of the pin round which the specimen is bent shall be in accordance with the appropriate value given in Table 3 below. The effect on the specimen shall be stated.

TABLE 3.

| Limits of Thickness of Specimen, inch | Diameter of Pin, inch |
|---|---|
| Up to and including 0·010 .. | $\frac{1}{2}$ |
| Above 0·010 to 0·020 .. | 1 |
| Above 0·020 to 1/32 .. | $1\frac{1}{4}$ |
| Above 1/32 to 1/16 .. .. | $1\frac{3}{4}$ |
| Above 1/16 to $\frac{1}{8}$ .. .. | 2 |

## RESEARCH TESTS.

### (7) ELECTRIC STRENGTH.

NOTE.—The following methods for the determination of the electric strength are recommended when the characteristics of the pressboard are not known, and when a thorough investigation is required to ascertain the electric strength of the material under probable service conditions.

(*a*) *General.*

It is of primary importance that the recognized electric strength be that of the material when hot and under long continued stress.

It is desirable to test pressboard at temperatures appreciably above its intended working temperature.

(*b*) *Conditioning of Pressboard previous to Test.*

As the electric strength of pressboard is largely influenced by the moisture content, the characteristic curves referred to later shall be obtained for as many as possible of the following conditions :—

(i) *Normal Condition.*—This is obtained by permitting the pressboard to absorb its normal quantity of moisture by exposing it to an atmosphere of 75 per cent relative humidity at a temperature between 15° C. and 25° C. for 18 to 24 hours.

(ii) *Dry Condition.*—This is obtained by removing from the pressboard as much as possible of its free natural moisture by heating it at a temperature between 75° C. and 80° C. for 18 to 24 hours.

(iii) *Damp Condition.*—This is obtained by exposing the pressboard to an atmosphere of 100 per cent relative humidity at a temperature between 15° C. and 25° C. for 18 to 24 hours.

(iv) *Tropical Condition* (*for use when required*).—This is obtained by exposing the pressboard to an atmosphere of 100 per cent relative humidity at a temperature between 45° C. and 50° C. for 18 to 24 hours.

NOTE.—If in (ii) or (iii) the pressboard is removed from the atmosphere of specified humidity before testing, precautions must be taken to prevent appreciable change in electric strength from this cause.

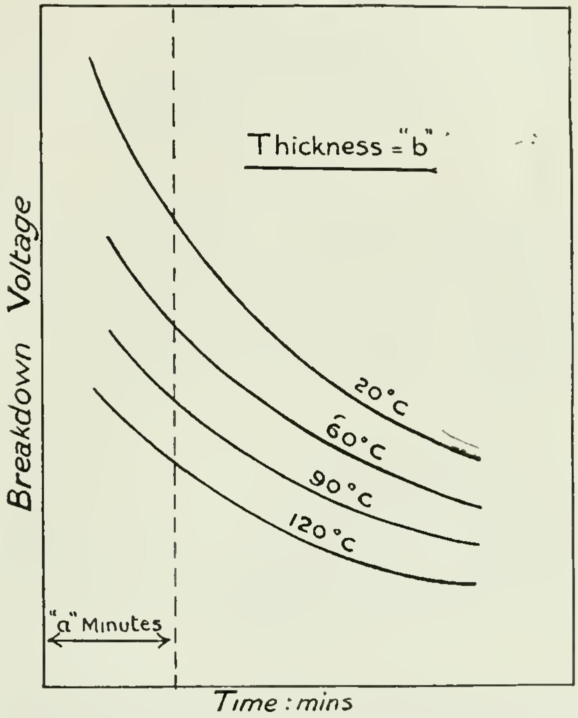


FIG. 3.—Time-voltage Curves at Various Temperatures.

When testing pressboard at the temperatures given in paragraph (*f*), the electrodes should be raised to the high temperature before the material is removed from the atmosphere of specified humidity.

(*c*) *Tests in Air or Oil.*

The electric strength tests on pressboard shall be carried out in air unless the material is intended for use in oil-immersed apparatus when tests under oil are permissible. In the case of pressboard intended for use in air and also in oil-immersed apparatus the effect of subjection to a damp atmosphere (paragraph (*b*) (iii)) on the electric strength shall be ascertained in air and in oil.

(*d*) *Method of Expressing Electric Strength.*

A single value for the electric strength of pressboard is of practically no use unless the time of application of the voltage, the temperature, and the thickness of the material are either stated or clearly indicated.

Instantaneous values obtained on a rapidly applied test are usually very high and misleading, being out of all proportion to the electric strength obtained by the sustained conditions of practice.

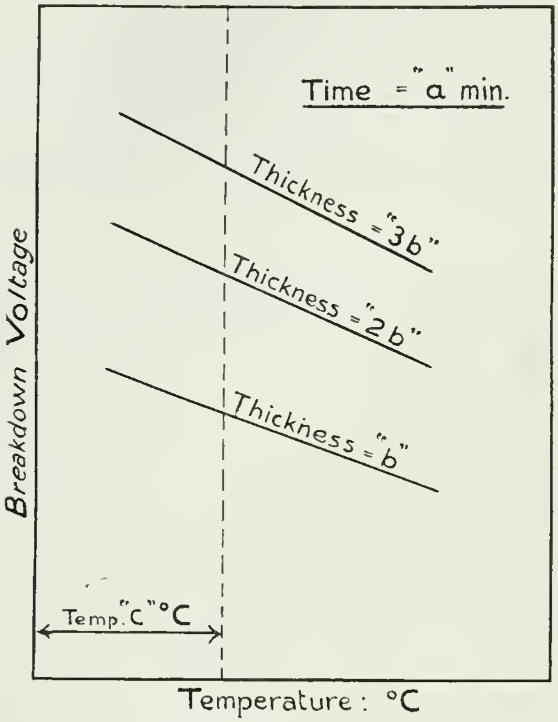


Fig. 4.—Temperature-voltage Curves for Various Thicknesses.

The electric strength shall be given in the form of a series of curves, in which the actual breakdown voltage, R.M.S. value, is plotted against time and temperature; as shown in Figs. 3 and 4 respectively, and the volts per mil against thickness as shown in Fig. 5.

(*e*) *Time-voltage Curves.*

(i) Electric strength tests shall be carried out so as to obtain time-voltage curves showing the breakdown voltage over the time range from half a minute to the time required for the breakdown voltage to become approximately independent of the time.

Note.—When the specimen is tested hot the time required for the breakdown to become approximately independent of the time of application of the voltage may be about 10 minutes. When, however, the tests are carried out at air temperatures (about 20° C.) the time may be considerably longer.

(ii) In special cases transient voltage tests may be desirable.

(*f*) *Temperature-voltage Curves.*

Time-voltage curves shall be obtained for the following temperatures :—

20, 60, 90, and 120° C. (see Fig. 3).

For a selected number of time values on the time-voltage curves a temperature-voltage curve shall be drawn similar to Fig. 4.

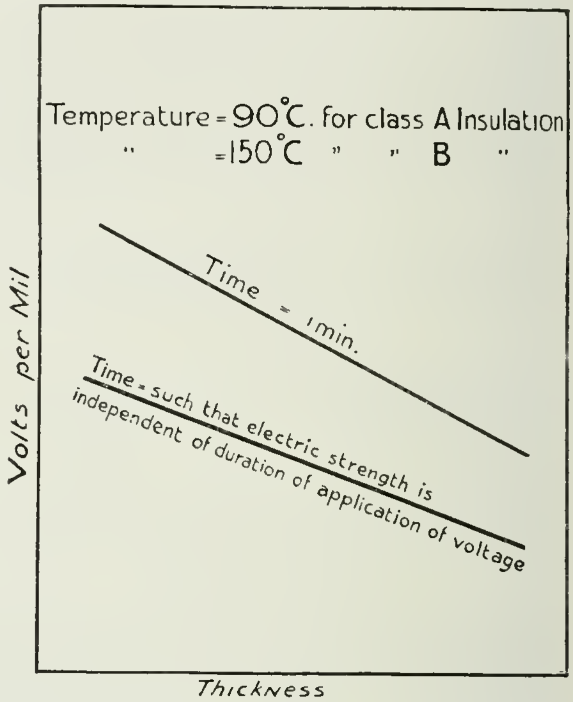


Fig. 5.—Curves showing the relationship between Electric Strength and Thickness.

(*g*) *Thickness-voltage Curves.*

(i) When the pressboard is supplied in more than one thickness sufficient temperature-voltage curves (Fig. 4) shall be obtained to enable the thickness-voltage curve to be plotted for definite time and temperature conditions (see Fig. 5).

(ii) One of the thickness-voltage curves shall be plotted from the one-minute values and another from the values at which the breakdown voltage is approximately independent of the time ($x$) during which the voltage is applied (Fig. 5).

Note.—For both the above curves the recognized standard temperature is 90° C. for B.E.S.A. Class A insulation.

In plotting the thickness-voltage curves, the values on the vertical axis should be expressed in volts per mil, and not in terms of breakdown voltages.

(*h*) *Calculation of Electric Strength.*

(i) *Curves.*—For drawing the time-voltage curves sufficient tests shall be made to enable fair curves to be drawn over the time range under investigation.

In order that some indication may be given of the uniformity of the material, all the experimental values shall be shown, and when considerable variation is found, this fact shall be specially mentioned.

Note.—As the temperature-voltage curves are taken from the mean curves drawn through the values obtained on the time-voltage tests, the experimental points cannot be indicated on these or on the thickness-voltage curve.

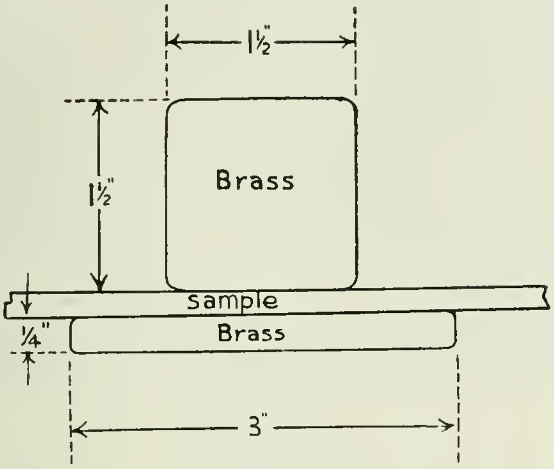


Fig. 6.—Electrodes for Electric Strength Test.

(ii) *Measurement of Thickness.*—The thickness of the pressboard shall be determined, as specified in Clause 14, by means of a suitable micrometer.

(*j*) *Test Equipment.*

(i) *Output of Testing Set.*—The output of the testing set shall be sufficient to maintain on the sample under test the necessary voltage for the maximum period required.

(ii) *Frequency, Wave Shape, etc.*—The frequency of the supply voltage shall be approximately 50 cycles, and if different its value shall be stated. The wave shape shall be as near sinusoidal as possible, and the conditions of the test such as to prevent any high-frequency oscillations.

Note.—In carrying out electric strength tests the voltage should be increased smoothly, preferably by means of a suitable resistance in series with the field of the alternator. When the voltage is varied by means of a resistance in series with the primary of the testing transformer the wave shape is liable to be distorted. If the wave shape is not known to be satisfactory, it should be checked whilst a sample is under test, and near the point of breakdown, by means of either a spark gap or a crest voltmeter.

(*k*) *Electrodes.*

The bottom electrode shall consist of a flat disc of brass 3 inches diameter by ¼ inch thick.

The top electrode shall consist of a solid cylinder of brass 1½ inches diameter by 1½ inches long.

The sharp edges shall be removed from the electrodes, but the radius at the edge shall not exceed 1/32 inch (see Fig. 6).

Note.—If the surface of the pressboard is irregular, or any difficulty is experienced in obtaining good contact, tinfoil should be interposed between the electrodes and the dielectric.

## ABRIDGED TESTS.

Note.—The following methods for the determination of the electric strength of pressboard are recommended when it is not required to ascertain the characteristics of the material under all of the conditions provided for above.

(*l*) *Conditioning.*

(i) Prior to test the materials shall be exposed to the "Normal" atmosphere as described in paragraph (*b*) (i).

(ii) If it is claimed that the pressboard has special non-absorptive properties, it shall also be tested after exposure to either "Damp" or "Tropical" conditions, as described in paragraph (*b*) (iii) and (iv).

(*m*) *Method of Expressing Electric Strength.*

The recognized method of expressing the electric strength of pressboard subjected to these abridged tests shall be the voltage required to produce breakdown in one minute when the material is at a temperature of 90° C. For ease of comparison the volts per mil, followed by a statement of the thickness to which it refers, shall also be given.

Note.—In the past it has usually been the practice to take the electric strength of an insulating material at air temperature, and by a rapid application of the voltage. Until the recognized standard of one minute at 90° C. has come into general use, it may occasionally be desirable for comparative purposes to determine also the electric strength when the voltage is rapidly applied at air temperature.

(*n*) *Time-voltage Curves.*

In order that the voltage required to produce breakdown in one minute may be accurately determined, the following procedure shall be adopted:—

A test shall be carried out by increasing the voltage as fast as is consistent with obtaining satisfactory readings of the measuring instrument. The pressboard shall then be subjected to two-thirds of the breakdown voltage obtained on a rapidly applied test, and the time required to produce breakdown noted.

From the results of this test an approximate value can be obtained of the voltage that will produce breakdown in about one minute ; and this estimated voltage shall then be applied and the time required to produce breakdown noted. From this latter result a still closer approximation can be made. In addition to the rapidly applied test, at least five punctures shall be obtained on each sample and the values plotted on a time-voltage curve, similar to Fig. 3, but for the time range round one minute only. From the curve the voltage required to produce breakdown in one minute can be determined.

(*o*) *Other Factors.*

In conducting the abridged tests for electric strength, the conditions specified for the other factors entering into electric strength tests are the same as for the research tests dealt with above.

### (8) Shrinkage and Swelling.

A specimen 6 inches square shall be cut from the material as received, and the length, width, and thickness measured.

The length and width respectively of the specimen shall be the mean of ten measurements taken at points equally spaced along each of two edges at right angles.

The thickness of the specimen shall be the mean of ten measurements of thickness taken at points equally spaced around the edges. The measurements shall be made by means of a micrometer or other suitable method.

Shrinkage shall be determined by the following methods :—

(*a*) The specimen shall be dried for 48 hours by heating uniformly in an oven at a temperature from 105° C. to 110° C., and the length, width, and thickness shall then be measured as above.

Comparison shall be made between the mean values of the dimensions before and after the heat treatment, and the percentage difference computed on the original mean values respectively shall be stated, the original mean values being given.

(*b*) The diameters of a ring approximately 4 inches internal diameter and 6 inches external diameter shall be measured longitudinally and transversely. The ring shall be immersed in transformer oil, complying with British Standard Specification No. 148 for light grade oil, at a temperature from 105° C. to 110° C. for 120 hours. The diameters shall then be re-measured as before at atmospheric temperature. Comparison shall be made between the values of the diameters before and after the immersion in oil, and the percentage difference computed on the original values shall be stated.

The thickness of the ring shall be measured at ten equidistant points around the circumference before and after the immersion in oil. Comparison shall be made between the mean thicknesses before and after the immersion in oil, and the percentage difference computed on the original mean thickness shall be stated, the original mean thickness being given.

Swelling shall be determined by the following method :—

The square specimen used in the shrinkage test shall be exposed to a jet of steam at a temperature from 105° C. to 110° C. for 6 hours and the thickness re-measured as before.

Comparison shall be made between the mean thicknesses before and after the exposure to steam, and the percentage difference computed on the mean thickness after drying shall be stated.

### (9) Freedom from Chemical Reaction.

The material shall be tested for freedom from acids and alkalis in the following manner :—

Cut up 30 to 40 grammes of the dried material into small pieces, care being taken to separate the various layers thoroughly. Weigh off duplicate samples of 10 grammes each, introduce each into a 250 cm³ flask and add 200 cm³ of distilled water. Boil gently for about one hour, allow the solution to cool, and then filter at the pump. Wash each sample of pulp twice with 75 cm³ of warm distilled water, then titrate the filtrates, using methyl orange as indicator, employing one sample for the acidity test and the other for the alkalinity test.

The solution shall show no sign of acidity.

If the indicator shows the solution to be alkaline, titrate (neutralize) it with a standard centi-normal solution of hydrochloric acid :—

$$\left(\frac{N}{100}HCl\right)$$

The pulp shall be again similarly treated repeatedly until the filtrate requires only 2 or 3 cm³ of—

$$\frac{N}{100}HCl$$

to neutralize it. A " Blank Test " of the water shall be made in a similar manner and allowed for if necessary.

The number of cm³ of the standard centi-normal solution of hydrochloric acid $\left(\frac{N}{100}HCl\right)$ required to neutralize 10 grammes of the material shall be stated.

Note I.—The presence of glue or albuminous matter may vitiate the result to some extent.

Note II.—The test specified above indicates mineral acids only. If the total acidity of the material is required, including organic acids which may be present, the method outlined above should be slightly modified by boiling the material in methylated spirit instead of in distilled water, and by titrating with phenolphthalein in place of methyl orange.

### (10) Freedom from Conducting Particles and Pinholes.

These tests shall be carried out by one of the following methods :—

(*a*) *Thick Materials.*

In the case of materials thicker than 1/16 inch, a specimen 6 inches × 4 inches shall be photographed by X-rays. The number of metallic particles and pinholes per square foot shall be stated.

(*b*) *Thin Materials.**

In the case of materials up to and including 1/16 inch thick specimens not less than 12 inches square shall be tested by the following methods :—

(i) The specimen shall be saturated with a dilute solution of hydrochloric acid, specific gravity approximately 1·1, and then immersed in a potassium ferricyanide solution to precipitate the iron present. Each iron particle will produce a blue spot on the paper.

The number of deeply stained particles per square foot of the specimen shall be stated.

(ii) A 1 per cent solution of silver nitrate shall be applied to the surface of the specimen. Each metallic particle will produce a black spot on the specimen.

The number of black spots per square foot of the specimen shall be stated.

(iii) The specimen shall be dipped into a 1 per cent solution (by volume) of acetic acid, and then allowed to air-dry for one hour while lying flat on a cloth.

When dry the specimen shall be dipped again in a solution containing 0·1 cm$^3$ acetic acid and 0·1 gm of potassium ferricyanide in 100 cm$^3$ distilled water.

Each metallic iron particle will produce a blue spot on the specimen, and each copper, brass, or gunmetal particle a red spot.

The number of blue and red spots respectively per square foot of the specimen shall be stated.

NOTE.—The potassium ferricyanide solution should be tested before use with some precipitated ferric hydroxide dissolved in strong nitric acid, and diluted with water. The potassium ferricyanide solution should give no blue precipitate or coloration.

### (11) FREEDOM FROM SUPERFICIAL DEFECTS.

The surface of the material shall be examined and its condition with regard to smoothness, uniformity, freedom from cracks, flaws, and other superficial defects shall be stated.

### (12) EFFECT OF OIL.

A specimen shall be immersed in transformer oil complying with British Standard Specification No. 148 for light grade oil for seven days continuously at a temperature from 100° C. to 105° C., and shall then be bent longitudinally and transversely through 90°. The diameter of the pin round which the specimen is bent shall be in accordance with the appropriate value given in Table 4 below. The effect on the specimen shall be stated.

### (13) WATER ABSORPTION.

The specimen shall be conditioned in accordance with Clause 1 before the test for water absorption is carried out.

A specimen 3 inches square shall be weighed. The specimen shall then be immersed in water at room temperature. After 24 hours' immersion it shall be taken from the water and, after removing the surface moisture by wiping, weighed again.

The specimen shall then be replaced in the water, and after six days' immersion re-weighed with the same precautions as before. The weight shall be taken to the nearest milligramme in each case.

The percentage absorption of water in each case shall be computed on the original weight of the specimen.

### (14) DETERMINATION OF THICKNESS.

The specimen shall be conditioned in accordance with Clause 1 before the thickness is measured.

TABLE 4.

| Limits of Thickness of Specimen, inch | Diameter of Pin, inch |
|---|---|
| Up to and including 0·010 . . | ½ |
| Above 0·010 to 0·020 . . | 1 |
| Above 0·020 to 1/32 . . | 1¼ |
| Above 1/32 to 1/16 . . . . | 1¾ |
| Above 1/16 to ⅛ . . . . | 2 |

Measurements of thickness shall be made by means of a suitable micrometer at ten points equally spaced around the sides of the sheet. The maximum, minimum, and mean values of thickness shall be stated.

### (15) DETERMINATION OF DENSITY.

The specimen shall be conditioned in accordance with Clause 1 before the density is determined.

The density expressed in terms of weight in grammes per cm$^3$ shall be ascertained by weighing a specimen 3 inches diameter, or 3 inches square. The usual precautions shall be observed in weighing the specimen, and the weight shall be taken to the nearest milligramme.

The area of the specimen shall be computed, in the case of the disc, from the mean of ten measurements of the diameter at equidistant points around half the circumference, and in the case of the sheet from the mean of ten measurements of the length and the width respectively at points equally spaced along each of two edges at right angles. The thickness shall be determined by making ten measurements with a suitable micrometer equally spaced around the circumference in the case of the disc, and around the sides in the case of the sheet, and the mean value shall be taken in computing the volume of the specimen.

---

* The hydrochloric acid in test (i) has a tendency to act upon the iron oxides present, thus producing considerable discoloration of the specimen. Test (i) does not readily disclose the presence of copper and brass particles.

Test (ii) detects iron, copper, and brass particles, but it is not sufficiently penetrating especially when testing a dark specimen, and metallic particles well inside the sample may not be disclosed. Also, after a short time the discoloration extends throughout the specimen, thus causing difficulty in detecting the metallic particles.

## III. APPENDIX.

### Method of Ascertaining the Electric Strength of Pressboard when Subjected to Long Application of A.C. Stress.

When in service in electrical machinery and apparatus, the pressboard has to withstand voltage stresses for long periods of time. As the pressboard is usually in contact with metal parts, which, on account of the energy losses in the copper and the iron, are at a higher temperature than the insulation, the conditions are such that any heat generated in the pressboard itself cannot be readily dissipated.

To investigate the internal heating produced in pressboard when under A.C. stress, and to ascertain the highest A.C. stress which the material can endure without loss of insulating property as the result of excessive internal heating, the following test is recommended :—

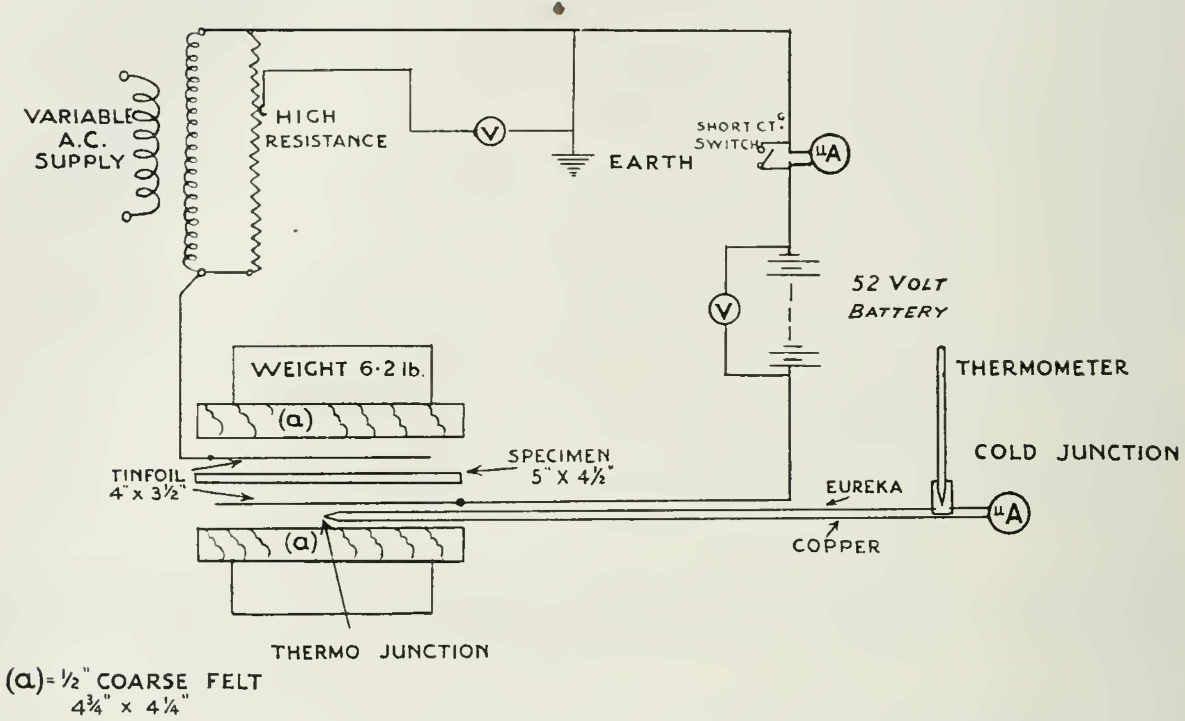


Fig. 7.—Connections for ascertaining the Electric Strength of Pressboard when subjected to Long Application of A.C. Stress.

(*a*) *Apparatus Suggested.*

In Fig. 7 is shown a diagram of the connections of the necessary apparatus. Particulars of a set of instruments that have been used for this test are given below :—

*A.C. Voltmeter.*—Electrostatic, reading to about 120 volts, capable of being connected across various sections of a suitable potential dividing resistance connected across the transformer secondary.

Note.—Any other type of high-voltage measuring equipment may be used.

*D.C. Voltmeter.*—Reading up to 150 volts in scale divisions of 1 volt.

*Microammeter.*—For measurement of leakage current. Robert W. Paul, London, N.K. 1 035.
Resistance : about 900 ohms at 20° C.
Range : 0–24 microamps, by 0·2 (120 scale divisions).

Note.—If the A.C. component is large an instrument of low resistance may be desirable.

*Thermocouple.*—Eureka—copper.

6½ inches each of 0·008 inch covered wire and hard soldered to form couple. At the other end the copper is soldered to 3 feet 8 inches of 0·027 inch covered copper wire, and the eureka to 3 feet 8 inches of 0·018 inch covered eureka wire.

From here copper flexible leads are connected to the instrument.

A thermometer is bound to the cold junction with tape.

Resistance = 4·734 ohms at 20° C.

A eureka series resistance can be inserted to increase the range, but this is not required, except for readings in the unstable range.

Resistance of couple and series resistance = 8·65 ohms at 20° C.

*Thermocouple Instrument.*—Microammeter by Robert W. Paul, London, N.I. 1 135.
Resistance = 5·1 ohms at 20° C.
Range, 0–300 microamps by 5 (60 scale divisions).
Temperature range :
Without series resistance : 0 to about 65° C. rise.
With series resistance : 0 to about 90° C. rise.

*Air Temperature.*—By thermometer 3 inches from edge of specimen, with bulb on the same level.

*Felt Pads.*—Coarse green felt, $4\frac{3}{4}$ inches × $4\frac{1}{4}$ inches × $\frac{1}{2}$ inch.

*Tinfoil.*—4 inches × $3\frac{1}{2}$ inches × 0·0015 inch thick.

(*b*) *Arrangement of Test.*

The material is cut into rectangles, each 5 inches × $4\frac{1}{2}$ inches, and exposed to " Normal " * condition (Clause 7 (*b*) (i) ). After conditioning, sufficient of these to form a pad approximately 30 mils thick are carefully laid and pressed together so as to exclude entrapped air. On each side of the pad a tinfoil 4 inches × $3\frac{1}{2}$ inches is pressed into contact. The specimen with its tinfoils is placed between two $4\frac{3}{4}$ inch × $4\frac{1}{4}$ inch pads of $\frac{1}{2}$ inch coarse felt, and mounted for test as shown in Fig. 7. A thermocouple in contact with the centre of the lower tinfoil measures the temperature attained. In series with the source of high-voltage A.C. are a D.C. battery of (usually) 52 volts and a microammeter by which unidirectional leakage current is measured.

(*c*) *Method of Test.*

An A.C. stress of definite moderate gradient (volts per mil thickness) is applied and maintained until temperature and leakage current attain steady values. The gradient is then increased, and again held until results are steady. This procedure is repeated until a gradient is reached at which temperature and leakage current will not settle down to steady values, but rapidly increase to a destructive condition. At this stage, unless interrupted, charring and complete breakdown rapidly follow. The microammeter should be short-circuited, or the voltage switched off before breakdown of the specimen takes place.

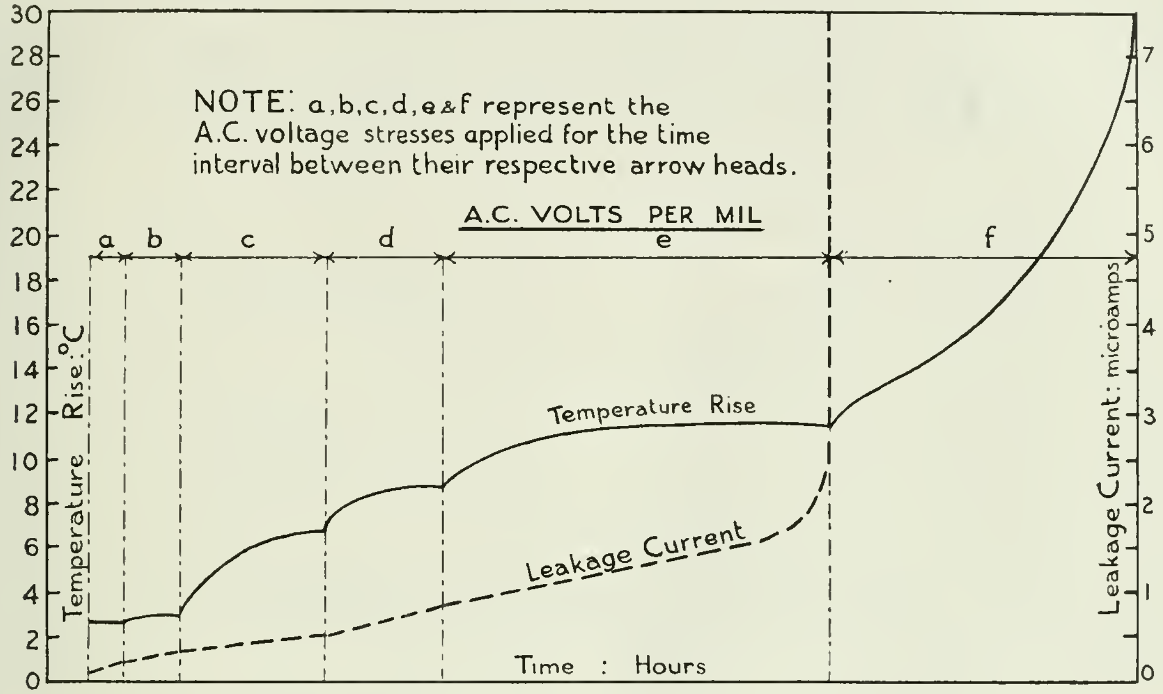


FIG. 8.—Method of expressing the Results of the Test shown in Fig. 7.

(*d*) *Method of Expressing Results Obtained.*

The values obtained should be shown graphically as illustrated in Fig. 8. The following should also be recorded :—

(i) Maximum voltage and electric stress in volts per mil, at which the material is in a stable condition.

(ii) Maximum temperature-rise obtained in (i).

---

* If it is claimed that the pressboard has any special non-absorptive properties, tests should also be made on specimens that have been exposed to " Damp " or "Tropical" conditions respectively (clause 7 (*b*) (iii) and (iv) ).

# DISCUSSION ON "THE INTERCONNECTION OF ALTERNATING-CURRENT POWER STATIONS." *

WESTERN CENTRE, AT CARDIFF, 6 NOVEMBER, 1922.

**Major E. I. David:** This paper is particularly interesting to the engineers of this district, where a number of interlinking schemes between power stations are under consideration. After seeing the large-scale maps of the enormous distribution schemes in America, one feels how trivial are local schemes in proportion to these, but the actual problems to be solved are very similar, and the paper is most helpful for that reason. I think that the line between Britannia and Aberaman was the first extra-high-tension line between two fair-size power supply systems in this country. At present operating at 20 000 volts, it is designed for 33 000 volts, and will shortly be changed over to that voltage. It connects two systems, one having six power stations and the other two, these being interlinked by their own systems. Power factor control is effected by means of a booster available at one end. In connection with this line an interesting series of figures were taken, and these are shown in Fig. J. The line was run with the receiving end open-circuited, but both step-up and step-down transformers, and also the booster, were in circuit. The pressure at the receiving end was varied by altering the boost from minus 105 volts through zero to plus 185 volts, the voltage at the generating end varying from 3 145 volts to 3 435 volts due to this variation of boost, and the busbar voltage being maintained constant at 3 250 volts. Under the latter conditions the pressure at the receiving end was 10 650 volts, the transformer secondary ratio at this end being normally 20 000/10 000, and 3 000/20 000 at the step-up end. The astonishing fact is that a magnetizing current as high as 395 amperes was required for the line under maximum boost conditions. As the energy losses were very small, the power factor meter of the line was practically at zero throughout the whole of the test. The station load was approximately 4 000 kW and the station power factor varied in the manner shown in the figure. The only possible explanation which I can give for this enormous magnetizing current is saturation of the iron in the transformers, as the latter were running at approximately 15 per cent above their rated voltage. Perhaps the authors can give some additional information. The one fact clearly illustrated by the paper is that, provided a station has any means of fixing its busbar voltage, the power factor of the supply which it takes, either from an interconnecting line or from an ordinary supply company's main, is entirely independent of the power factor of its own load, and as the general policy of station engineers is to carry as little wattless current as possible, the result will be to maintain such a busbar voltage that the generating station power factor will be as near unity as possible, and the supply company will have to deal with this. Unless, therefore, the busbar voltage of all interconnected stations is under the control of the

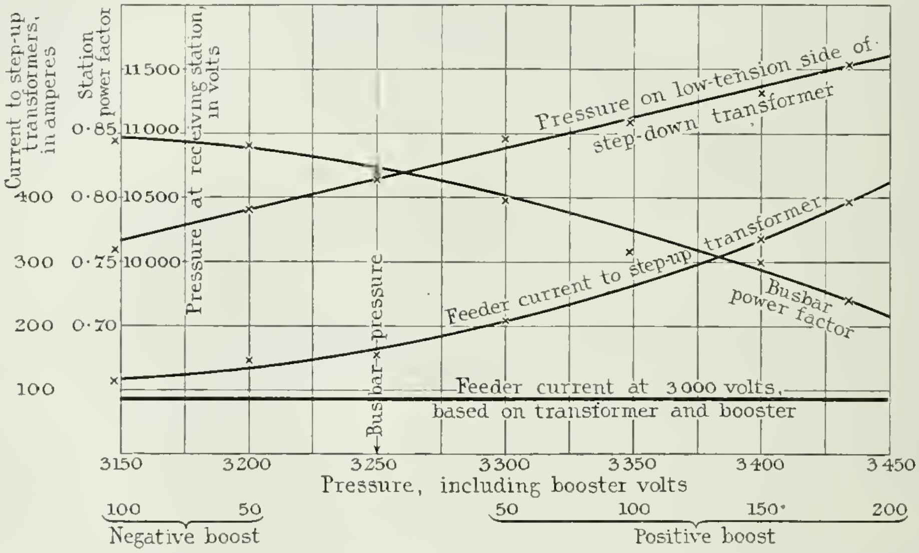


Fig. J.—Open-circuit currents, power factors and voltages on a 10-mile, 20 000-volt, three-phase, 50-period transmission line. Two 3 300-kVA, 3 000/2 000-volt step-up transformers; two 3 300-kVA, 20 000/10 000-volt step-down transformers; three single-phase boosters giving ± 6 per cent boost.

---

* Paper by Messrs. L. Romero and J. B. Palmer (see vol. 60, pages 287 and 803).

main load despatcher, it will be seen that, even where stations belong to the same company, trouble must ensue, and where stations belong to companies having only interchange of current arrangements the difficulties will be extremely great. Table 1 shows that under certain conditions the receiving station has to produce kilovolt-amperes corresponding to the kilowatts of its energy load at a power factor of 0·29, which would entail either abnormal generators or synchronous condensers. The authors appear to favour running this particular interconnecting line at the normal power factor of the load, with boosters to correct the busbar voltage. In all other cases, synchronous condensers would be necessary at the receiving end, as it is hardly likely that station B could deal with the enormous kVA loads at low power factors. One point which has not been considered is the question of providing the wattless kVA by large synchronous motors driving plant on the load side of station B. Under these conditions the charges for wattless energy should not be as great as those shown in Table 2, and transmission of power at unity power factor might be shown in a more favourable light. There appears to be a considerable discrepancy between the formula produced in Stone's paper * and the authors' formula for synchronizing power. Stone's formula gives the synchronizing power in kW for each degree deflection from the normal phase angle. The essential factors of the two formulæ are the same, i.e. $E_1E_2X/Z^2$, but the remaining factor is entirely different in the two cases. Possibly the authors could give a mathematical reason for the difference. At the same time the actual value of this factor is of small importance until a value is decided upon for the synchronizing power necessary for two power stations. Stone gives values varying from 1 to 1·5 times the capacity of the smaller plant to be paralleled. By a slight variation of this factor it appears that the two formulæ might be brought into agreement. The factor has, of course, to be varied to suit the different kinds of prime movers, as the synchronizing capacity necessary with a gas engine which occasionally misses an explosion must be very different from that in the case of a turbine with its uniform turning moment and sensitive governing gear. In our case we have a gas-engine station interconnected with several other stations and we find no difficulty in running in parallel, but we do find that there is a great tendency for the gas engine to be the first to trip out on a surge caused by a fault in any part of the system. At all times the synchronizing currents passing in this interconnecting link are large and have a definite periodicity which corresponds to the speed of the gas engines, and during periods of light load in the interconnecting link actual reversals of power take place during each revolution. Should the synchronizing power of a line at any time be found unequal to the task of keeping two stations in parallel, a simple remedy is to increase the pressure of the line, as the synchronizing power increases practically as the square of the line voltage.

**Mr. I. Jones**: Dealing with a few points which are met with on interconnected systems I might mention that on the system with which I am associated there are high-pressure and mixed-pressure turbo-generators, together with reciprocating low-speed gas-engine generating sets all working in parallel, and no practical difficulties are experienced in the satisfactory load adjustments of the different stations. Efficient telephonic communication is maintained between them, so that transfer of loads or other changes of running conditions can be satisfactorily arranged. In dealing with the parallel operation of the system the question of load adjustment depends, as the authors have pointed out, on the governing characteristics of the prime movers, but the question of pressure adjustment between the systems interconnected is quite a different problem, especially where the interchange of power may be in either direction and where there are large fluctuations in the load. The voltage adjustment on this system is obtained as stated in condition (3) on page 288 (vol. 60), but there are occasions when one or other of the stations has to deal momentarily with a fair amount of extra wattless current, due to varying load conditions at the consuming centres. My experience with automatic voltage regulators working with interconnected stations has not been very satisfactory, under conditions such as those mentioned above, especially in cases where they had to work as ordinary voltage regulators, but we obtained far better operation after they had been fitted with a compensating coil, being thus rendered practically power-factor regulators for the generators to which they were connected. I should like to hear the authors' experience with automatic voltage regulators on such systems. With reference to synchronizing power, I should like to know if the authors consider it necessary to have a tie line between a reciprocating or gas-engine station and a turbo-generator station of larger synchronizing power than that between two turbo-generator stations. On a number of occasions I have noticed that on the occurrence of a disturbance due to fault conditions the gas-engine generators nearly always come off the busbars first although not feeding directly into the fault. In the case of a tie line 9 miles in length connecting two of our largest power stations, at the point where it is connected with one of our main consuming centres we have no difficulty in synchronizing, speed and voltage adjustments being arranged by telephone. Have the authors met a case where it has been impossible to synchronize a tie line at some remote point on an interconnected system due to a displacement of the phase voltage?

**Mr. W. Nairn**: There does not seem to be much scope for interconnection between modern power stations in this country where electricity is generated from coal. Although at first sight it would appear to be very comforting to have an interconnector of large capacity between two modern power stations, yet in practice the advantage is very limited, the restricting factor being the supply of steam. Take the case of two power stations, A and B, equipped with 10 000-kW sets and with a 10 000-kW interconnector between them, and consider what happens when station A drops 10 000 kW of load, due to a set suddenly going out of commission. The 10 000 kW is supposed to be picked up by the interconnector and carried by station B, but what really happens is that as soon as B takes over the load the steam pressure begins to drop and B trips out the interconnector in order to safeguard the consumers in its own area. During the failure the supply undertaking finds itself in the position of having a 10 000-kW interconnector, at the one end of which is 10 000 kW of steam and no generating plant and, at the other end, 10 000 kW of generating plant and no steam. Of course it might be argued that in the event of a serious defect such as a "strip" or a "burn-out" in station A, the interconnector would be of substantial advantage, but the fact is that the money expended on the interconnector would be very much better spent in providing additional generating plant in station A. I cannot dismiss from my mind the idea that a power station is essentially an establishment for the generation and export of electrical energy and that it is no part of its business to import electricity, and I also feel that when expensive distribution cables are laid it should be into districts where there is no electricity supply and not into the heart of a generating station. From this point of view I consider the paper to be very valuable, as I believe that in some instances interconnectors have been installed without due regard to the facts which the authors have so clearly set out.

---

* *Transactions of the American Institute of Electrical Engineers*, 1919, vol 38, p. 1651.

**Mr. J. H. Thomas**: There has been a point of apparent importance mentioned in the discussion in connection with the magnetizing current of transformers and motors as affecting the power factor. I was associated with a station generating at 3 300 volts, 50 periods, three-phase, and a number of motors wound for 3 000 volts were connected to the system. After a time the generating pressure was raised to 3 500 volts. The result was that the power factor of the station was lowered owing to the greater magnetizing current of the motors at the increased voltage. It was found that the power factor could be increased from 0·6 to 0·7 by lowering the voltage at the generating station so that the motors worked at the pressure for which they had been designed. The same point would of course apply to transformers, and this is of particular interest in the case of interconnected systems, as mentioned by the authors, who state that the voltage is widely varied. It seems to me that it would be generally a question of interconnection between systems in this country, and that under these conditions the best method of operation would be to transmit at unity power factor irrespective of the loads, and to obtain regulation by means of synchronous condensers. These can, I believe, be supplied with automatic regulators varying the excitation so as to obtain unity power factor on interconnecting lines. It is of great importance that motors and transformers should work at the pressure for which they have been designed.

**Mr. D. Jenkins**: Recently I met with a case very similar to that mentioned by Major David. I allude to the heavy excess currents observed by him when the voltage was increased on a line loaded only by an unloaded transformer. In my case the consumer took power at 33 000 volts through a transformer transforming down to 3 300 volts, and carrying almost exclusively an induction motor load. With the transformer secondary open the 33 000-volt circuit breaker was switched in and set to operate at about 700 kVA. The 3 300-volt switch was then closed. As soon as an attempt was made to start up a 100-h.p. slip-ring induction motor by means of a liquid starter, the high-tension switch tripped. This occurred three or four times in succession. On looking into the matter it was found that the high pressure was considerably in excess of 33 000 volts, and it was concluded that the heavy magnetizing current taken by the motor at this excess voltage was sufficient to trip the breaker. It will be noticed that the disproportion between the starting current of the induction motor under normal conditions and under these excess voltage conditions is even more extraordinary than that observed by Major David. It is true that in his case the load was an unloaded transformer, whereas in mine it was a transformer loaded only by an induction motor. Essentially, however, the load conditions are the same, in that we both have a pure induction load. Undoubtedly an excess voltage greatly increases the magnetizing current, especially if the induction plant is designed to work well up on the "knee" of the magnetization curve. No mention has been made in the paper about the interconnection of supply systems of different periodicities. At the present moment I am interested in interconnecting a 25-period and a 50-period supply. The necessary frequency changer would, when converting either way, have to run in parallel with other synchronous generating plant. I should be glad to know whether the authors have had any experience of such conditions. Is such a frequency changer a satisfactory and reliable proposition?

**Mr. J. W. Fidoe**: The subject of the paper is of particular interest in this district as we have a number of interlinked industrial power stations, and other interconnections are under consideration. The operation of two or more power stations in parallel has certain advantages as far as continuity of supply is concerned, but the maximum of economy would appear to be obtained where it is possible to find other undertakings having an inverse load curve, under which condition stand-by plant is reduced to a minimum. Our colliery plants carry their maximum load between 7 a.m. and 3 p.m., whereas during the remainder of the day the generators seldom carry more than $\frac{1}{3}$ load. It would be very satisfactory if we were able to sell power to local authorities for lighting and other purposes, the demand for which would be mostly after 3 p.m. For a colliery to sell power instead of coal means a change of policy, but in view of the amount of idle plant the matter is well worth consideration. The power factor of the supply is a fruitful cause of dispute, and there is evident need of a central authority to give definite orders as to the running conditions of the stations, otherwise each engineer naturally attempts to regulate his end of the line so as to carry as little as possible of the wattless current. In the examples given by the authors the overhead interconnector naturally occupies a prominent position, but in this country we are not favourably situated either as regards climatic conditions or legal restrictions. In South Wales we have a further trouble with high-tension lines which have frequently to be carried across hilly country where they are very exposed. The south-westerly gales carry saline matter which gradually accumulates on the porcelain insulators and occasionally causes breakdowns. The use of step-up transformers is not an unmixed blessing, and where possible it is preferable to generate at a pressure high enough to render them unnecessary for the short interconnectors which are the general rule in this district.

**Professor F. Bacon :** I regard the paper as being most interesting and important from the points of view of both theory and practice. I, too, cannot help feeling that the magnitude and extent of the transmission systems in America make operations in this country appear comparatively trivial. One must look to such schemes as Major David mentioned, in which electrical power generated in the South Wales coalfield would be transmitted to London, to readjust the balance. Enterprise in the United States must be greatly aided by the wonderfully high overall annual load factor obtained. In this connection the table on page 297 (vol. 60) is most striking. I am sure that it would prove of general interest if the authors would explain how it is that load factors of 65 per cent and even 80 per cent are secured in America, whereas many of the biggest stations in this country have to operate at a load factor of between 20 and 30 per cent.

**Messrs. L. Romero** and **J. B. Palmer** (*in reply*) : In reply to Major David the excessive magnetizing current, which he observed at no load and maximum boost on the line he describes, must have been due, as he says, to too high a flux density in the transformer cores, and this would not of course occur if the transformers were designed for the highest voltage to which they would be subjected in practice. It is fair to point out, however, that Major David's transformers would probably never in ordinary practice be subjected to the conditions which he mentions, as maximum boost would not be required under no-load conditions. We believe that the formula in Mr. Stone's paper gives far too high a value for the synchronizing power, although, as we have not a copy of his paper by us at present, we are unable to point out exactly where we disagree. Our own formula is worked out mathematically step by step in the Appendix to the paper, and its accuracy has not been seriously challenged.

In reply to Mr. Jones, the effect of automatic voltage regulators at the two interconnected stations is to accentuate the power factor variations of the current in the line, as the load in the line varies. If automatic regulators are not in use, the arithmetical difference between the two busbar voltages will tend to vary with variations of the load in the interconnecting line in such a way as to minimize the variations in the power factor of the line current. That is to say, automatic voltage regulators give inflexible voltage conditions under which the line power factor will depend solely on the line characteristics and load, while without such regulators the voltage conditions are somewhat more flexible. We are certainly of opinion that a larger line synchronizing power is needed between a gas-engine station and a turbine station than between two turbine stations.

There is considerable force in the point made by Mr. Nairn as to what would probably happen if one of the generating sets in one of two interconnected stations were suddenly to go out of commission ; but we would point out that if a larger number of power stations were interconnected, sufficient steam supply would probably be available to tide the system as a whole over such an accident. We are in agreement with Mr. Nairn if his contention is that the transmission of large blocks of power can only be justified when there is substantial economy to be effected by it. Recently one of the authors had occasion to investigate the question of how far from the load area it would pay to erect a projected power station in order to obtain greater generating economy by erecting it on a tidal river, the price of coal and coal-handling facilities being equal in both cases. In other words, the problem resolved itself into a comparison of the generating costs of a station having cooling towers, and one having an unlimited water supply, but with the necessity for transmitting the whole of its output. The economical distance proved to be remarkably small, as the greater efficiency of the riverside station would be offset by a comparatively small expenditure on transmission cables and the cost of supplying the transmission losses. At the same time it must not be overlooked that when dealing with existing power stations the cost of an interconnector may be amply justified by the economies incident to the improvement of the plant load factors of one or both stations, and the authors believe this to be one of the chief incentives which have brought about the interconnections already effected in this country. We would qualify Mr. Nairn's statement that a power station is essentially a plant established for the generation and export of electrical energy. In our opinion a power company or a municipality is chiefly concerned with the sale of electrical energy, and the source from which it derives the power it sells is a secondary consideration. On the assumption that an interconnection is economically sound, it would often happen that the " heart of the generating station " of the receiver system would be the only point at which the bulk supply could be efficiently received. If it were possible to interconnect through the networks of the respective systems it would obviously be advantageous to do so, but the authors' experience is that there are many cases where the only point in a network at which it is possible to receive a large block of power is the power station busbars.

Mr. Thomas, and subsequently Mr. Jenkins, refer to the variations in power factor caused by varying voltage on feeders which are not necessarily interconnectors. This is, as they suggest, caused by the saturation of the iron circuits of induction motors and transformers, and goes to show that in designing interconnections it is necessary that the effects of voltage variation should be carefully considered when deciding on the system of operation and fixing the constants of the interconnector. Mr. Thomas is probably correct in saying that the best method of operation would be to transmit at unity power factor irrespective of the load; and to obtain regulation by means of synchronous condensers. The question is, however, one of cost and quality of service required, and can generally be decided by balancing the cost of regulating apparatus to ensure the transmission at unity power factor against the disadvantages of poor voltage regulation and cost of increased transmission losses involved by transmission at some power factor less than unity.

Mr. Fidoe refers to the economy which would be obtained if it were possible to find other undertakings having inverse load curves. In this country this condition will be the exception rather than the rule, but with colliery plants carrying their maximum loads between 7 a.m. and 3 p.m. it should be possible to effect economies by supplying energy to a power company or local authority having a heavy lighting load. We have remarked both in the paper and in the discussion at other Local Centres on the necessity for the running conditions of interconnected stations being under the control of one person, otherwise the divergent ideas of individual station operators as to the power factors and load factors at which they should operate would almost certainly result in confusion. The question of overhead versus underground transmission lines does not come within the scope of the paper, but after having seen and noted the success of overhead transmission and distribution in the United States and Canada, one cannot but feel that the overhead system has not yet been thoroughly tried out in this country.

In reply to Professor Bacon the transmission systems and interconnections in the United States are naturally on a very much larger scale than anything we have in this country, but it would be a mistake to think that our transmission and distribution systems are trivial in comparison. In our opinion the problems which have had to be faced by British undertakings, both company and municipal, are just as difficult both from the financial and technical standpoints as anything that the American companies have encountered, excepting, of course, that their operations have been on a very much larger scale than ours. It is true that the load factors obtained by the American concerns assist very considerably in the finance of the huge transmission systems which are common in America. The high load factors are brought about by a number of reasons.

The very heavy financial outlay required to construct hydro-electric plant and long transmission lines can only be justified by a load having a diversity factor which no single city could offer by itself, and this has brought into existence large power companies whose interests cover very wide areas. Many of the cities are of comparatively recent growth with no strongly entrenched competition from gas and steam in existing industrial plants. Railways are electrically operated in the United States to an extent we have only just begun to think about in England, and, as far as the Pacific States are concerned, irrigation offers a heavy off-peak load. Domestic load is most carefully fostered by the power companies and various associations formed for the purpose, and it is apparent that the propaganda which is most assiduously carried on has been very effective.

# THE MEASUREMENT OF THE ELECTRIC INTENSITY OF RECEIVED RADIO SIGNALS.

By J. HOLLINGWORTH, M.A., B.Sc., Associate Member.

[Communicated by permission of the Radio Research Board.]

(From the National Physical Laboratory.)

(*Paper first received* 18*th December*, 1922, *and in final form* 24*th March*, 1923; *read before the* WIRELESS SECTION 7*th February*, 1923.)

### SUMMARY.

The first part of the paper is devoted to a discussion of some of the principles on which the measurement of received signals is based, and the practical application of these principles under working conditions is considered.

The latter part describes a system recently developed at the National Physical Laboratory which differs in several details from previous systems. Its operation is described in detail, and some of the possible sources of error and inaccuracy are considered.

## I. PRINCIPLES AND THEIR PRACTICAL APPLICATION.

This problem is one of the most fundamental in radiotelegraphy and has received attention from large numbers of experimenters.

It is one which forces itself on everybody concerned with radio operation, as well as on those interested in the more scientific aspect of the subject. Many theories as to the cause of signal-strength variations have been suggested, and owing to the complexity of the circumstances involved it seems very unlikely that these variations will ever be expressed in a general mathematical form covering all cases; but the work of Austin has shown that, under specified conditions, a workable expression can be obtained.

For this purpose the primary need is a very large number of observations under known conditions, so that the first problem is the production of measuring apparatus the limitations of which are fairly definitely determined.

Prior to the introduction of the thermionic valve the instrumental difficulties in the way of experimenters were enormous. Beyond the small range available if direct-reading instruments were used, the only possibility of measurement was by a method involving some form of crystal detector; and, although the sensitivity of the latter is fair, the uncertainty and difficulty of calibration are a great handicap.

Such a method was indeed used by Austin * in his investigations which led up to the introduction of the Austin-Cohen coefficient; but for the longer ranges, which are the most interesting from the theoretical point of view, some more sensitive form of receiver is essential.

For measurements at very short distances a direct method is practicable. This usually consists of the insertion of a delicate thermal instrument, such as a Duddell thermo-galvanometer, into a tuned aerial or coil circuit the constants of which are known, the instrument being calibrated by direct current.

Such experiments, which have recently been considerably developed by Vallauri * and Pession,† serve a rather different purpose, their object being to determine the effective or radiation height of an aerial. For this purpose the measurements must be made at so short a distance from the aerial that the attenuation is negligible, with the result that the received signals are comparatively strong. In all cases the problem reduces to the determination of the current induced in an aerial system of known constants, from which either the potential gradient or the magnetic field at the receiving circuit can be calculated. Before the days of continuous waves the problem was further complicated by the decrement. In the resulting calculations the decrements of both the sending and receiving circuits are involved, and the determination of these alone is nearly as difficult as the original problem. With the advent of the triode with its possibilities of amplification and continuous-wave generation, the scope was very much enlarged and new methods became possible. As soon as an amplifier has to be used, however, it becomes necessary to employ some form of substitution method, because the absolute calibration of an amplifier is not at present practicable. This inevitably increases the chances of error, always very numerous, as is known by everyone who has attempted radio-frequency measurements; the result is that any method must appear to be more or less a compromise, and without extended trials and tests it is very difficult to give a decision as to which is the most satisfactory. In many cases practical considerations are of considerable weight, and from this point of view the following requirements must be borne in mind, in addition to all those of a theoretical nature :—

(*a*) The actual operation should be as rapid and simple as possible.

(*b*) Special transmission should be reduced to a minimum.

(*c*) The overall calibration should be effected as closely as possible under working conditions.

(*d*) The set should be moderately portable and capable of adaptation to varying conditions.

(*a*) and (*b*) are strictly practical questions; but they play a very important part in problems of this nature, for the case is rather different from that of a purely scientific measurement in which the whole operation is under the immediate control of the experimenter, who can repeat readings or vary his conditions as often as required. Even if the transmitting aerial be entirely devoted to the experiment its remoteness renders its detailed control difficult, and in many cases altogether impossible, with the result that the measurements must be made either on the routine transmission or on a short, special signal sent for the purpose. Observations seem to show that the first of these is not of much value except for very rough measurement, owing to the continual and irregular variations produced by the keying ; and even if it be possible to obtain a reading of some sort at the receiving end, owing to these variations it is difficult to correlate it with the reading of the transmitting-aerial ammeter. If a special signal be used, working conditions demand that it should cause as little interference as possible with the ordinary routine.

---

* *Bulletin of the Bureau of Standards*, 1911, vol. 7, p. 295.

* *Radio Review*, 1921, vol. 2, p. 77.

† *Ibid.*, p. 228.

This is the chief objection to a method devised by Lieut. Guierre,* in which a series of timed signals are required from the transmitting station, they being synchronized with the signals from the local oscillator. This method certainly enables various other serious difficulties to be overcome ; but the organization required for an extended series of measurements on these lines would be very elaborate.

For the same reason it must be possible to obtain the readings rapidly ; the set must be capable of being adjusted in working order before the commencement of the special signal, and fine adjustments must be reduced to a minimum. For instance, in the " URSI " signals the whole time available is two minutes, although the preliminary tuning-up of the set in the case of " UA " (Nantes) allows a certain margin for adjustments.

(*c*) and (*d*) are primarily questions of design, though (*d*) involves policy also. In this connection there are two alternatives. Either measurements of as high accuracy as possible may be made, involving a large amount of apparatus and a very highly skilled operator, observation points being, of course, very limited in number ; or the apparatus may be in such a form as to permit of multiplication and distribution to a larger number of observers, in order to obtain simultaneous, though rather less accurate, readings. Considering the present state of our knowledge of atmospheric effects at the moment it appears that the latter method is the one from which the most useful information may be expected, and as it represents approximately the policy of the Radio Research Board, under whose direction the whole of this work is being carried out, this advantage has been borne continuously in mind.

*Technical considerations.*—The following methods are in use :—

(*a*) Telephone methods.
(*b*) Galvanometer methods.

Under the former heading may be included what is known as the shunted-telephone method, in which comparative results are obtained by shunting the telephones until the signal just disappears ; but considerable difference of opinion exists as to the accuracy of this method, and in any case it is not high. In all other cases the received signal is balanced, either audibly or visually, against a calibrated, local source of oscillations, from the reading of which the incoming intensity can be calculated in the required form.

Telephones have the advantage of simplicity in use. They can be used in places where a galvanometer is impracticable or undesirable, and are familiar pieces of apparatus. Owing to their power of audible selectivity they can be used when jamming is present, though the accuracy of results obtained under such conditions requires confirmation. They also allow of the easy selection and identification of the station, and messages can be read until the last minute before taking the observation.

On the other hand, an audible method is comparatively insensitive to small variations in intensity. The author has shown * that the minimum change in intensity which can be detected under favourable conditions is about 2 per cent with spark signals. Experience tends to show that with continuous waves the figure is higher owing to the different quality of the note ; and it is probable that 5 per cent is the lowest which can safely be assumed for general working. With an audible method a heterodyne is necessary, and it has also been found that telephones have a considerable effect on the amplifier. This will be referred to later.

Galvanometer methods in general involve merely the replacement of the telephones by some form of d.c. indicating instrument. The chief advantage that they afford is greater sensitivity to small variations ; but it has been found from experience that they offer several other advantages, among which is the possibility of keeping the signal and its variations under continuous observation. On the other hand, the signal cannot be read directly unless an Einthoven instrument be used, and the power of audible selectivity is lost.

*Fundamental formulæ.*—Before proceeding to details it will be well to give the simple theory and the equations on which all substitution methods depend. Let $I$ be the current at the base of the transmitting aerial, $\lambda$ the wave-length, and $d$ the distance from the receiving station, assuming propagation over a plane conducting surface through a perfect dielectric ; then $D$, the vertical intensity of the electric field at the receiving station is given by :—

$$D = 120\pi \frac{Ih}{d\lambda}$$

where $h$ is the height of the ideal Hertzian half-oscillator which would produce the same effect as the actual transmitting aerial. It is usual to call $h$ the effective (or radiation) height of the aerial. Its value varies from about 50 per cent to 75 per cent of the actual height of the aerial, being dependent upon the form of the latter, the immediate surroundings, and also to a small extent upon the wave-length and various electrical factors. Now, if the potential gradient $D$ be applied to an aerial of effective height $h_1$ and high-frequency resistance $R_1$, the electromotive force induced in it is $Dh_1$, and consequently, if the aerial be tuned, the resulting current is $Dh_1/R_1$. In the case of a coil of area $a$, and number of turns $n$, the corresponding current is

---

* *Radio Review*, 1921, vol. 2, p. 621.

* *Radio Review*, 1921, vol. 2, p. 282.

$$2\pi Da\frac{n}{R_2\lambda}$$

$R_2$ being the high-frequency resistance of the coil (these results are based on the assumption that the wave front is vertical, whereas experience seems to show that this is frequently not the case).* If the wave front be tilted, coil reception will be unaffected, whereas reception by means of an aerial will be changed to an extent depending on the ratio between its horizontal and vertical dimensions. If the polarization be more complex, as often occurs when night effects are present, the intensity of reception in both coil and aerial will be varied, and in such cases the intensity measured has really the value of the equivalent, plane, polarized wave, rather than that of anything possessing an actual physical existence.

The usual method of calibration is to disconnect the aerial system at intervals and to connect the receiving set to a non-radiating aerial which has the same constants as the receiving aerial and contains a calibrated mutual inductance coupled to a calibrated local oscillating circuit; the latter is then adjusted until equality of signal strength is obtained.

The applied voltage is deduced from the known constants of the local circuit; and, from the formula given above, the potential gradient is derived. This method involves the equalization of the constants of the main and dummy aerials, and the accuracy of this adjustment will be one of the chief factors determining the accuracy of the result. In addition, on switching over to the dummy aerial, any jamming previously present will disappear, thus introducing another uncertain factor into the physiological balancing process. The question of jamming by an extremely powerful station of sufficiently different wave-length to be outside the limit of audibility is one which requires experimental investigation; but it seems likely that under such circumstances, unless the characteristic curve of the receiver can be taken as a perfectly straight line, modification of the position of balance will result.

Unfortunately, with the multiplication of high-power intercontinental stations, the above is becoming a very serious factor in working on weaker signals. These difficulties are largely overcome by the method used by Lieut. Guierre, in which the ordinary aerial is used for balancing, the distant transmission being so controlled that its periods of silence synchronize with the working period of the local oscillator. The objections to this system have been referred to above.

### II. The N.P.L. System.

*N.P.L. apparatus.*—The following apparatus has recently been constructed at the National Physical Laboratory with the object of undertaking measurements of this kind. A galvanometer method is used, the idea being to obtain greater sensitivity than is possible with telephones. In general principle it follows standard lines, but it exhibits several important modifications. Its chief features are:—

(*a*) No heterodyne required.
(*b*) No metallic screening necessary.
(*c*) Only one oscillating circuit in use at a time.

The signal from the tuned receiving circuit is applied in the usual way to a multi-valve resistance-capacity amplifier. A galvanometer is connected in the anode lead of the last valve and is made to give zero deflection for the normal anode current, a 2-volt cell and adjustable resistance across the galvanometer being used for this purpose. The incoming signal polarizes the grid of the last valve and in this way reduces its anode current, the reduction being indicated by the deflection of the galvanometer.

This is, of course, a standard method adopted by many workers. For calibration purposes the tuned receiving circuit is broken and totally disconnected from the amplifier, which is then joined to the local oscillator through a calibrated untuned coupling coil. The oscillator is next adjusted until the same deflection is obtained as with the signal.

The high-frequency resistance of the receiving circuit is also measured under actual working conditions by the movement of a switch. From this stage the calculation proceeds as before. The method differs from the normal one only in the use of an untuned circuit for calibration and in the internal design of the local oscillator; but in order to obtain reliable results great attention must be paid to a large number of small details.

### General and Constructional Details.

(*A*) *The aerial system.*—The method can be applied equally well to an ordinary aerial or a closed coil. For convenience and portability a closed coil has been adopted, though this is open to several objections, chief among which are the low absorption, especially on long wave-lengths, and the antenna effect. The former is due to the fact that with a vertical potential gradient $D$ the E.M.F. produced in an aerial is $Dh$, whereas with a coil it is $2\pi Dna/\lambda$. On the other hand, the directive property of a coil is often a valuable asset.

With regard to antenna effect, the behaviour of the whole coil as an aerial with respect to earth is an old and serious problem. In directional work it is one of the chief objections to the use of a plain revolving coil; but in this case one is working on the minimum of the coil E.M.F., so that the antenna effect is unmodified. In measurements where, of course, the maximum position of the coil is used, it only appears in conjunction with the coil E.M.F., but even then it requires consideration. In theory, since it flows in an untuned path it should be 90° out of phase with the true signal, provided the latter be accurately tuned. Actually, it may not be exactly 90° out of phase, and in this case it would have a component in phase with the signal. Now the characteristic feature of antenna effect in directional work is the great bluntness of the minimum, no sharp zero being discoverable. This effect can be caused only by the out-of-phase component, as the effect of the component in phase with the signal cannot be to blunt the zero but only to shift its position, since the antenna effect does not change sign as the coil passes through its zero position, whereas the coil E.M.F. does. Hence the well-known flat minimum proves that antenna effect has at least a considerable component 90° out of phase with the main signal. In the present case it can also be shown that any component in phase with the signal is small. Consider two positions of the coil 180° apart and not too near the maximum, in which case a signal of fair intensity is obtained. If the antenna effect be exactly 90° out of phase with the main signal the total E.M.F.'s in these two positions will be equal; but if the antenna effect have a component in phase with the signal the total E.M.F.'s in these two positions will not be equal, as the coil E.M.F. changes sign with the rotation through 180°, whereas the antenna E.M.F. does not. Hence the equality of the deflections at any two points 180° apart can be taken as a sign that any antenna effect present is 90° out of phase with the main signal.

---

* T. L. Eckersley: *Radio Review*, 1920, vol. 1, p. 422.

To verify this, an actual test was made on the Nantes "URSI" signal. The coil was set about 30° from its maximum position, so that a fair signal was obtained, but one which at the same time would be appreciably affected by the antenna E.M.F. A reading of the galvanometer was taken, and the coil was swung rapidly through 180°, when it was found that the galvanometer reading was unaltered. Other tests seem to indicate that the value of antenna effect present on Croix d'Hins (23 450 m) is about 10 per cent of the true signal, but accurate measurement on a station is difficult, owing to keying variations; and, of course, the effect cannot be obtained from a local continuous-wave buzzer.

If the above antenna effect be 90° out of phase with the main signal, the actual signal strength will be only $\sqrt{(100^2 + 10^2)}$, i.e. 100·5 approximately, an increase of only half of 1 per cent, which can be safely neglected.

It also seems likely that the absence of an operator and telephones tends to reduce the antenna E.M.F. In this connection the following facts have been noted repeatedly.

The anode circuit of the last valve contains a double-pole throw-over switch, by means of which it can be connected either to the galvanometer or to the primary of a telephone transformer. When listening-in with the telephones it is often possible to hear, in addition to the station sought, several stations on different wave-lengths, this being effected by correct adjustment of the heterodyne only; but, on changing over to the galvanometer and re-tuning, the required signal comes in with a pure resonance curve having zeros on either side.

Also, when working on the galvanometer, the mere touching of the telephones will produce large variations in the deflection, even though the telephones are isolated from the amplifier both by a transformer and by a double-pole ebonite-insulated switch. Moreover, the amplifier often oscillates violently when the telephones are being used, whereas with the same adjustments it is quite stable on the galvanometer. The above results seem to show that if care be taken with the design and arrangement of the apparatus the effect of antenna E.M.F. is not serious.

The coil now in use consists of a wooden box frame 5 ft. square, wound with 79 turns of 7/26 S.W.G. copper wire spaced $\frac{1}{8}$ in. apart. This is sectionalized by a three-way switch so that either 29, 50, or 79 turns can be used, the coils not in use being completely cut out. With suitable condensers the range covered is from 3 000 to 25 000 m, making allowance for the fact that for work of this type it is essential that a coil should not be worked near its natural wave-length.

Probably, for the measurement of very weak signals, a coil of greater area would be advantageous, but of course it would be less portable.

(*B*) *Amplifier*.—In general this consists of a multi-valve resistance-capacity amplifier of the usual type containing, however, several special arrangements.

Resistance-capacity coupling was adopted for three reasons :—

(*a*) *Larger effective wave-length range*.—A transformer amplifier, though more efficient over a limited range, cannot be made to cover a large one without the use of interchangeable transformers; and generally it has certain points at which it is very liable to oscillate. As the set is not designed to work below 3 500 m, the question of the inefficiency on short waves of such an amplifier does not arise.

There being no heterodyne effect, audio-frequency amplification is inadmissible.

(*b*) *No screening required*.—In measurements such as these it would be essential to screen all coils and transformers thoroughly in order to avoid inductive effects from outside stations or from other parts of the circuit, as such inductive effects might be completely altered when the change-over was made from outside station to calibrating circuit.

(*c*) *Stability*.—In dealing with measurements it cannot be too strongly emphasized that the prime necessity is stability of the apparatus. Sensitivity, amplification, and even selectivity must all give place to stability. The amplifier must be kept well away from regeneration, instead of, as is usual, working as near this point as possible. Of the short time available for taking a measurement there is none to spare for fine amplifier adjustments; and, for example, a six-valve set working inefficiently, but stably, is far preferable to a "super-efficient" three-valve pattern. (A great deal of work is being done in order to get the most suitable arrangement combining fair amplification with reliable stability and ease of adjustment, the details of which are rather far from the subject matter of the present paper.)

The above three reasons have led to the selection of a resistance-capacity amplifier, though under other conditions it is possible that one of another type would be more suitable.

The chief objection to an amplifier of this type is the poor working on low wave-lengths, i.e. with small values of the tuning condenser. This is a side issue of the more important fact that every valve circuit possesses an effective impedance, which forms a load on the oscillating circuit, and so reduces its effective voltage considerably.

This has been discussed in detail by the author in another paper,* in which it is shown that if the amplifier be considered as equivalent to a high resistance $R_1$

---

* *Wireless World and Radio Review*, 1922, vol. 10, p. 351.

shunted across the condenser (this is not strictly accurate, but avoids considerable mathematical complication) the effective resistance of the equivalent simple circuit is $R + \omega^2L^2/R_1$, $R$ being the ordinary high-frequency resistance of the circuit. Now, under ordinary conditions, with a large inductance and small condenser, $\omega L$ is large, so that it frequently happens that the first term is entirely swamped by the second; and as long as this holds, it actually pays to reduce the number of turns on the receiving coil and to increase the condenser value, since the loss of received energy due to the decreased area-turns is more than compensated for by the reduction in apparent resistance. For instance, the actual deflections of the galvanometer on a fixed signal of wave-length 9 100 m, using the three sections of the coil in turn, were of the same order; whereas the equivalent resistances were 6·5, 36 and 102 ohms, the corresponding d.c. coil resistances being 3·1, 9·0, and 12·1 ohms respectively. It appears from this that any measurement of high-frequency resistance should include the valve in working condition, especially when the ordinary circuit resistance is low.

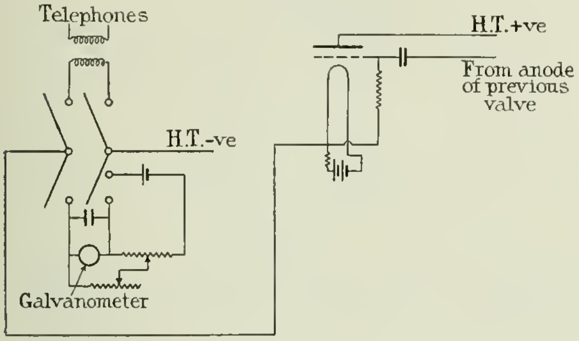


Fig. 1.—Connections of the last valve.

The special circuits in the amplifier are confined to the last valve (Fig.1). Instead of the usual telephones a sensitive galvanometer and shunt are connected in the anode circuit, and across them is placed a 2-volt accumulator with such an arrangement of resistances that the normal anode current can be balanced; the deflection is obtained by the departure from the normal, and the whole is shunted by a 5-$\mu$F condenser. Under these circumstances the effect of atmospherics appears to be small and, as a matter of fact, excellent results have been obtained during a thunderstorm.

The last valve is also run off a separate battery in order to minimize the creep of the zero due to the gradual fall of accumulator voltage on load; and for the same reason the filament resistance is a fixed one of the iron-in-hydrogen pattern. With these precautions, provided that the accumulator be in reasonably good condition, the creep of the zero is negligible except when working at the extreme limit of sensitivity of the galvanometer, a proceeding undesirable for many reasons. A double-pole throw-over switch is also provided so as to allow of the use of telephones for listening-in purposes.

In order to obtain satisfactory results with a balanced system of this type it is essential to use an accumulator and not a primary battery, and the resistances should be of a robust, stud pattern. In fact, such resistances should be used everywhere for work of this nature, as the slightly decreased elasticity, as compared with that obtained in the ordinary sliding, variable type, is more than compensated for by the increased steadiness and reliability.

Between the coil and the amplifier is the usual arrangement of tuning condenser and a throw-over switch (Fig. 2).

The latter connects the amplifier terminals either to the tuned receiving circuit or to the untuned calibrating coil, and by means of two auxiliary contacts the oscillating circuit is completely broken when the switch is in the second position. By a slight rearrangement of connections this switch can be made to introduce a dummy aerial when an audibility method is being used.

*The calibrated local oscillator.*—As has been mentioned above, the local source is connected to the amplifier by an untuned coupling circuit. In this way it is possible to dispense entirely with metallic screening, since there is never more than one oscillating circuit in action at a time.

Screening involves bulky and inconvenient apparatus, since the control must be either inside the screening box or brought out in a very careful manner, and the effectiveness of the operation is always open to doubt. Smith-Rose has shown * that in the immediate neighbourhood of a powerful amplifier the most elaborate screening precautions must be taken in order to ensure perfect protection, and that the difficulty increases with the wave-length.

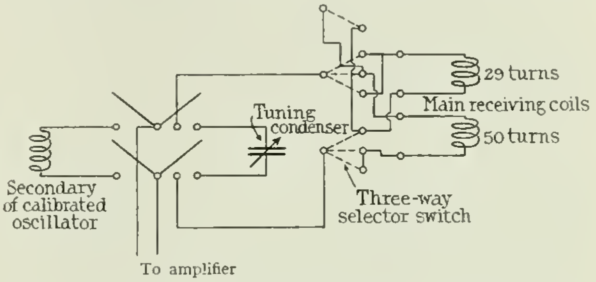


Fig. 2.—Tuning condenser and throw-over switch.

On the other hand, this method involves the necessity of actually measuring the effective high-frequency resistance of the receiving system at each observation; but the set is so arranged that this can easily be done, and the great advantage results that a very severe check on the accuracy and correct working of the apparatus is provided.

In the ordinary systems a dummy aerial, if used, must have the same constants as the receiving system so that the high-frequency resistance problem, though latent, is still present.

Methods which introduce the calibrating oscillation into the receiving aerial avoid this difficulty, but in this case the calibration cannot be carried out until the transmitting station has stopped, whereas both "UA" and "LY" carry on with their routine work after the special signal.

---

* *Proceedings of the Physical Society of London*, 1922, vol. 34, p. 127.

The oscillator itself has several special features. In the ordinary construction of such oscillators a normal continuous-wave generator is used with a high-pressure supply of 50 to 60 volts, so that the oscillating current is large enough to be measured on a direct-reading instrument. A few turns of the oscillating circuit are led through the primary of a variable mutual inductance ; but this arrangement involves the screening of the main part of the oscillator from the mutual inductance. Also it has been found that with the use of such comparatively high voltages there is a danger that an appreciable but indefinite amount of energy may reach the later valves of the amplifier owing to capacity coupling.

If, however, the whole of the oscillating inductance be used as the primary of the mutual, the secondary can be mounted some distance away from it, and this increase in distance and the reduction of the high-tension voltage minimize the risk of capacity coupling. This method involves actual measurement of the mutual inductance under working conditions, but this is practically essential in any case and is not difficult, whilst, with the control which will be described shortly, it is not necessary to rotate the secondary.

It is impossible to lose sight of the fact that in the normal oscillating circuit the current is not the same throughout. Prof. Howe has proved this in the case of a simple circuit ; and experiments have shown that in an actual oscillator, due to the presence of the reaction coil and other apparatus, the current distribution is much modified from the theoretical form. It is therefore necessary to take a definite point on the circuit as the point of reference and to express everything in terms of the current at this point. This may involve a variation of apparent mutual inductance with wave-length ; but as the mutual inductance must be determined experimentally in every case, the net result is merely to necessitate a slight wave-length correction in the apparent mutual inductance when working in the neighbourhood of the natural frequency of the oscillator.

A thermo-junction and galvanometer are connected, therefore, at any convenient point in the oscillating circuit, and all measurements are made with reference to this point. The high-tension voltage is controlled by means of a stud potentiometer so far as fine adjustments are concerned, coarse variations of the secondary E.M.F. being obtained by the use of a selector switch and a set of separate secondary coils. The instrument has been so designed that it can be fitted in a screened box for use with an audibility measurement, experiments having shown that, if the galvanometer have an iron case and be connected to the oscillator by screened leads, the leakage of oscillations is too small to cause trouble.

The secondary of the mutual inductance consists of several coils containing various numbers of turns. As the high-pressure control can be arranged to give a variation of slightly over two to one it is possible, by having several separate secondaries each containing about twice as many turns as the last, to get a very large variation of secondary E.M.F. and to retain the same percentage sensitivity on each range, the latter being an equally important advantage. The present range on 9 000 m is approximately from 5·0 mV to 0·05 mV.

*Calibration of receiving set.*—The formula for the results is derived as follows :—

From the second equation in Section I above we see that the current in an oscillating circuit with potential gradient $D$

$$= \frac{D \times 2\pi a n}{R\lambda}$$

Hence, the resonance volts on condenser, i.e. volts applied to amplifier

$$= \frac{D \times 2\pi a n \sqrt{(R^2 + \omega^2 L^2)}}{R\lambda}$$

Under ordinary conditions $\sqrt{(R^2 + \omega^2 L^2)}$ may be replaced by $\omega L$,

$$\therefore \text{ resonance volts} = \frac{2\pi a n D \omega L}{R\lambda} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Since the local oscillator is then adjusted so as to give the same deflection as the incoming signal, we must have :—

Resonance volts = volts applied to amplifier by local oscillator,
= $\omega I_0 M$, where $I_0$ is the current in the local oscillator, and $M$ the mutual inductance between it and the coupling coil.

$$\text{Hence} \qquad \frac{2\pi a n D \omega L}{R\lambda} = \omega I_0 M \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\therefore D = \frac{I_0 M R \lambda}{2\pi a n L}$$

$M$ being the appropriate value of the mutual inductance for the particular wave-length and secondary coil employed.

In connection with the local oscillator the following important point has been found. Investigations on an oscillating circuit of this form showed that the oscillating current could be expressed in the form $I = A(\lambda + B)(V + C)$, where $\lambda$ is the wave-length, and $V$ the high-tension voltage, $A$, $B$, and $C$ being constants.

For some time this law was used to determine the current in order to avoid the use of a thermal measuring instrument, but it was found that the ageing of the valve was liable to affect the values of the constants slightly. It is quite possible that a valve could be artificially aged for this purpose, in which case a simple and rapid method of current measurement would result, but, pending the outcome of experiments to this end, a thermal instrument has been adopted. The immediate importance of the formula lies in the fact that in all cases $B$ appears to be small compared with $\lambda$.

Hence, if $I = A(\lambda + B)(V + C)$

$$\omega I M = A(\lambda + B)(V + C)M \times 3 \times 10^8/\lambda \times 2\pi$$

i.e. the term involving $\lambda$ is $(1 + B/\lambda)$

Now, for the shortest $\lambda$ employed, $B/\lambda$ was of the order of 0·1, so that even a 10 per cent change in the wave-length adjustment of the local oscillator only produces a change of about 1 per cent in the secondary voltage.

Hence, accurate tuning of the local, calibrated oscillator is unnecessary; it can be used to heterodyne and to read the incoming signal, and then be used without further adjustment for calibration. This effects a valuable saving of time at a period when every second is of importance.

*Determination of M.*—As has been mentioned above, $M$ is not necessarily the mutual inductance measured by low-frequency methods, but the mutual inductance at working frequency referred to the current at a particular point on the oscillator. It is measured as follows :—

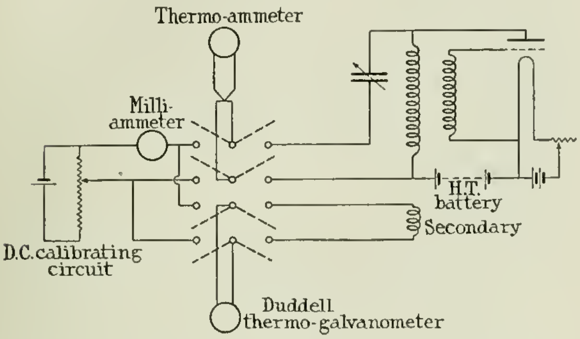


Fig. 3.—Diagram showing calibration of oscillator.

The oscillator is connected as in Fig. 3, the Duddell thermo-galvanometer with an appropriate heater being in the secondary circuit, and an ordinary thermo-junction and galvanometer in the oscillating circuit. The primary voltage must generally be higher than the usual value, in order to give a readable current in the secondary. It is assumed that on any given wave-length the current distribution in the coil is unaltered by this increase in voltage, and this seems probable as there is no grid condenser to alter the potential of the reaction coil. Also, the curve for $M$ (Fig. 4) shows that that function has a practically constant value for the higher wave-lengths, so that the variation of distribution must be small. The resistance and impedance of the secondary are measured by ordinary methods, since its natural frequency is so high compared with those under consideration as to have no measurable effect. In addition, the secondary is of a form in which the increase of resistance with frequency is small, and as a high-resistance heater is generally required in the thermo-galvanometer this variation can be neglected.

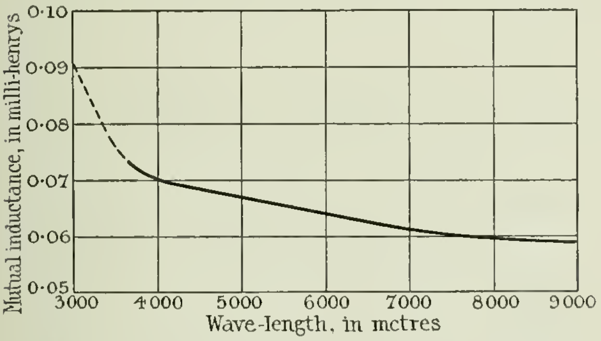


Fig. 4.—Value of mutual inductance in calibrated oscillator.

Owing to the use of the untuned coupling it is necessary to measure the high-frequency resistance of the circuit for each observation. While this introduces an apparent complication into the process of taking a reading it has several very definite advantages, these being :—

(1) No assumptions of uncertain accuracy are made.
(2) A very severe check on the correct working of the apparatus is provided for each reading.
(3) Owing to there being no balancing circuit the number of turns on the coil can be varied at will. This is of value if it is required to take observations of stations on widely different wave-lengths with only a short interval of time between them. In addition, it is sometimes advantageous to have control of the resistance.

As before mentioned, the variable factor in each case is the amplifier itself, owing to its power absorption, and it seems likely that this property must persist even if filter circuits are used, as the power to operate the amplifier must be derived from the receiving circuit either by direct conductivity or by induction. The effect of the amplifier depends, of course, on its adjustment, and it is possible to make the loss excessively small or even negative, so obtaining regeneration.

For measurement purposes, however, either of the latter conditions is liable to produce great instability; a slight change in the strength of the incoming signal may completely alter the amplifier characteristics, and where accuracy is required it is far safer to eliminate any regenerative possibility.

In general, the more stable the amplifier the higher its power absorption, so that it is necessary to consider both of these factors; but it must be borne in mind that comparatively high power-absorption does not necessarily mean poor amplification, so that the critical factor is often not sensitivity but selectivity, which brings back the old problem of interference. The absence of a heterodyne destroys the power of audible selectivity, though the accuracy of results obtained when this power has to be exercised requires further investigation.

There is but little difficulty in reducing the total resistance of the circuit to about 10 ohms, which gives a fair degree of selectivity, and the case only becomes serious when an attempt is made to measure a weak station with a high-power station very much nearer to the place of measurement. This can be best illustrated by drawing a tuning curve.

Take, for instance, the case of "GBL" which, with 180 amperes in the aerial, at 8 350 m may be expected to give an E.M.F. of 400 $\mu$V in the coil at Teddington. Assuming the resistance of the receiving circuit to be 20 ohms and its inductance 10 500 $\mu$H, Fig. 5 gives the lower part of the tuning curve neglecting any antenna effect. It will be seen, therefore, that for a station giving an E.M.F. of 40 $\mu$V, if a measurement of the latter be required to an accuracy of even 20 per cent, the closed range of wave-length is from 7 600 m to 9 100 m approximately. Now, suppose a similar measurement to be made by the audibility method. If the heterodyne note of Leafield be just inaudible the small station would give a good working note if its frequency differed from that of Leafield by about 3 000, i.e. if its wave-length were 9 120 m. But at this wave-length the high-frequency E.M.F. of Leafield would be 50 per cent of that of the incoming, small signal, so that unless it were certain that the amplifying power of the high-frequency side of the amplifier were unaltered by a 50 per cent increase in applied E.M.F. an error would be produced when the circuit was changed over to the calibrating source, in which no such extra E.M.F. was present.

Except under such conditions it is an advantage to use a circuit of higher resistance as the tuning is far less critical. Until a galvanometer be used one does not appreciate how critical is the tuning of a circuit of even moderately high resistance, the reason for which being, of course, the comparative insensitivity of the telephones to small changes in intensity. For instance, in Fig. 5 a variation of 10 per cent in intensity is caused by a variation of 0·25 per cent, i.e. 4·5 $\mu\mu$F, in the capacity of the condenser. It is also important to know what error is likely to be produced if accidentally the receiving circuit be slightly out of tune with the signal under measurement. This is most likely to occur for small values of the tuning condenser where the adjustment is finer. Considering, however, the coil data given above, it can be shown by calculation that an error of 1 per cent in the condenser value, though it reduces the actual galvanometer deflection to about 45 per cent of its maximum value, only reduces the measured value for the potential gradient by 5 per cent.

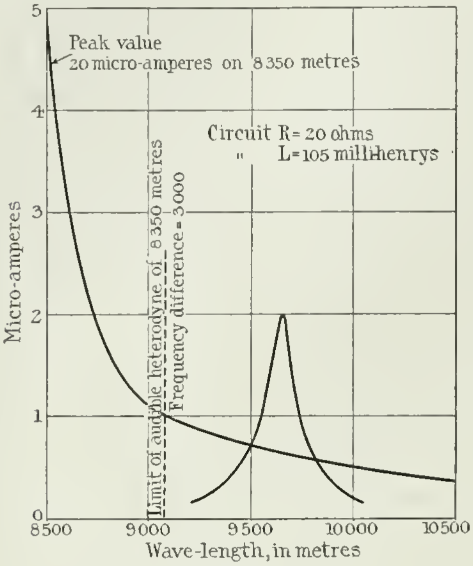


FIG. 5.—Tuning curves.

The actual measurement of resistance is made as follows. The coil is fitted with a five-way switch by which resistances of 7·46, 18·3, 39·9, and 78·2 ohms can be inserted in the oscillating circuit. A signal, either from a local source or from outside, is tuned, and readings of the galvanometer are taken for all five positions of the switch. The voltages corresponding to these readings are then measured by the local, calibrating circuit, the resistance being calculated in the usual way.

From these results very important information can be obtained. Of course, if the resistance of the circuit be unusually high or exceptionally low the extreme values of the inserted resistance may not give accurate results, but the group has been so chosen as to be suitable for average working. In a particular case the following results have actually been obtained. By using the five steps and working out the results of individual pairs the following series of values for the high-frequency resistance of the circuit was found: 22·3, 22·9, 22·75, 22·35, 23·8, 23·2, 22·4, 22·3, 21·5, the average of these being 22·6 ohms; the above values are as consistent as may be expected from measurements of this nature under ordinary conditions.

Their close agreement shows the truth of the following statements:—

(*a*) The effective resistance of the amplifier is independent of the signal strength.

(*b*) Since the calculation of these results involves the figures obtained for the various mutual inductances of the secondary coils, these figures must be accurate.

(*c*) Any direct electrostatic coupling to the amplifier is negligible, since the constants in (*b*) were obtained with a thermo-galvanometer and not by means of the amplifier.

In connection with (*a*) it is interesting to note that if the amplifier be forced, this series breaks down abruptly, showing that at a certain point self-oscillation commences. Cases occur in which the values obtained with the larger resistances in series are quite normal, but an abrupt variation occurs when the added resistance is cut out. There appears some evidence in support of the idea that the amplifier resistance varies with the signal strength when close to this state.

A series of this nature is by no means exceptional, but, of course, in order to obtain such a one reasonable care must be taken to get everything into a steady state. In actual working on a definite routine it is seldom necessary to take the entire series, as a single reading is sufficient if it be known that the apparatus is working stably. It is also possible in the case of a special signal to measure the resistance by means of a local source immediately before the transmission commences. This will remain constant throughout the signal, if the duration of the latter be not too great, so that the whole time of reception can be devoted to watching and recording the momentary variations.

It appears from these results that the slight extra complication involved in measuring the resistance is more than compensated for by the very severe test applied to the apparatus in the process; and a definite indication of the accuracy of the result is obtained.

In fact, it appears from experiment that, provided the amplifier be in a stable state, its equivalent resistance on any given wave-length is definitely determined by the adjustments, filament current, high pressure, etc., and that by the measurement of these the total resistance of the coil can be foretold without actual measurement, each time an observation is taken. Of course, owing to possible slight changes in valves, and leaks, it would not be safe to dispense entirely with resistance measurement after having determined it once; but if in the course of a series of observations, through unforeseen circumstances a few measurements of resistance are missed, the values can be obtained from other readings in which the state of the amplifier was the same.

*Measurements of the URSI Signals from Nantes (UA) made at the National Physical Laboratory.*

| Date | Potential gradient $\mu$V/m | Effective *R* of set | Date | Potential gradient $\mu$V/m | Effective *R* of set |
|---|---|---|---|---|---|
| **1922** | | ohms | **1922** | | ohms |
| Oct. 25 | 1 100 | 10·5 | Dec. 1 | 1 670 | 17·7 |
| ,, 26 | 1 980 | 14·0 | ,, 4 | 3 200 | 20·8 |
| ,, 27 | 2 190 | 23·0 | ,, 6 | 2 310<br>2 030 | 21·0† |
| ,, 31 | 1 660 | 16·6 | | | |
| Nov. 1 | 2 100 | 9·8 | ,, 7 | 2 050 | 19·4 |
| ,, 2 | 4 260* | 14·7 | ,, 11 | 1 600 | 21·3 |
| ,, 10 | 2 720 | 12·6 | ,, 12 | 1 800 | 18·0 |
| ,, 14 | 3 270 | 19·4 | ,, 14 | 1 730 | 21·7 |
| ,, 15 | 1 750 | 9·3 | ,, 18 | 1 650 | 14·8 |
| ,, 16 | 2 000 | 16·7 | ,, 20 | 1 010 | 10·0 |
| ,, 17 | 2 250 | 19·2 | ,, 21 | 1 360 | 13·0 |
| ,, 20 | 1 040 | 30·0 | ,, 22 | 2 269 | 15·8 |
| ,, 21 | 1 900 | 23·7 | **1923** | | |
| ,, 22 | 1 795 | 42·5 | Jan. 3 | 1 720 | 20·0 |
| ,, 27 | 2 440 | 16·0 | ,, 4 | 2 200 | 21·2 |
| ,, 28 | 1 760 | 16·4 | ,, 5 | 1 460 | 17·7 |
| ,, 29 | 1 420 | 21·4 | ,, 8 | 840 | 6·3 |
| ,, 30 | 1 950 | 17·6 | ,, 10 | 3 100 | 28·0 |

* Obviously an abnormal day. "MSK" (Moscow) was heard loudly on a small set on which it is normally inaudible during the day. Daylight variations of bearing were also reported as excessive.

† An abrupt change of intensity occurred in the middle of the signal.

NOTE.—These figures are the actual readings obtained and are not corrected to the standard aerial current of 180 A for purposes of comparison. The variations are in most cases not more than 2 or 3 per cent.

On the basis of the Austin-Cohen formula the theoretical value of the gradient at the N.P.L. with 180 amperes in the aerial should be 1 760 $\mu$V per metre.

Wave-length 9 000 m. Time of transmission 2.15 p.m.

In order to verify the fact that the result was independent of the particular adjustment of amplifier, a local oscillator was set up and its intensity measured. The amplifier was then considerably altered, i.e. the number of valves, high pressure, and filament current were changed, and the local source was measured again. The results differed by less than 1 per cent. The same effect has also been noticed when measuring the "URSI" signals, but, of course, in this case since 24 hours have to elapse between successive readings it is impossible to guarantee that the incoming signal remains constant to this degree of accuracy.

*General observations.*—The foregoing is primarily a description of the development of a system of signal-strength measurement. Time has not yet permitted of an extended series of actual observations, nor of a critical test against any other method. It is hoped to carry out both of these in the future, as until this is done it is impossible to make any very definite comparisons or to indicate which system is most suitable for any given conditions. It is also hoped to obtain useful information by the incorporation of an Einthoven string galvanometer so as to obtain photographic records of signals, which will assist in deciding another very important question, namely, within what limits of intensity and frequency an average transmission is liable to vary.

*Measurement of the URSI signals from Rome (IDO) made at the National Physical Laboratory.*

| Date | Potential gradient $\mu$V/*m* | Effective *R* of set | Date | Potential gradient $\mu$V/*m* | Effective *R* of set |
|---|---|---|---|---|---|
| **1922** | | ohms | **1923** | | ohms |
| Dec. 12 | 366 | 22·1 | Jan. 11 | 282 | 18·8 |
| ,, 13 | 455* | 22·0 | ,, 15 | 220 | 12·5 |
| ,, 14 | 210 | 18·2 | ,, 16 | 383 | 13·6 |
| **1923** | | | ,, 18 | 354 | 12·5 |
| Jan. 4 | 257 | 5·4 | ,, 19 | 88 | 2·0 |
| ,, 5 | 275 | 1·7 | ,, 22 | 270 | 11·3 |
| ,, 8 | 353 | 20·0 | ,, 23 | 341 | 13·5 |
| ,, 10 | 273 | 5·1 | ,, 26 | 277 | 13·2 |

* Poor reading.

Aerial current 100 A.

On the basis of the Austin-Cohen formula the theoretical value of the gradient at the N.P.L. is 153 $\mu$V per metre.

Wave-length 10 800 m. Time of transmission 5 p.m.

These investigations were carried out for the Radio Research Board, and the author has to acknowledge his indebtedness to the members of Sub-Committee A of this Board, detailed below, for much useful advice and criticism throughout the experiments.

*Members of Sub-Committee A of the Radio Research Board.*—Dr. E. H. Rayner, M.A. (*Chairman*). Admiral of the Fleet Sir Henry B. Jackson, G.C.B., M.C.V.O., F.R.S. (Chairman of the Board). Prof. G. W. O. Howe, D.Sc. Prof. E. H. Barton, D.Sc., F.R.S. Mr. D. W. Dye, B.Sc. Major J. Erskine-Murray, D.Sc. Prof. H. M. MacDonald, F.R.S. Mr. F. E. Nancarrow. Mr. J. Hollingworth, M.A., B.Sc.

Also he wishes to express his indebtedness to his assistant, Mr. H. A. Thomas, M.Sc., for his valuable aid in all the latter portion of the experimental work.

## Discussion before the Wireless Section, 7 February, 1923.

**Dr. J. Erskine Murray:** I am very pleased to see that this type of work has advanced so far. It has been for a long time among my special interests but its extreme difficulty has always beaten me, because I have never been able to give sufficient time continuously to the subject. The author's apparatus is comparatively simple and is evidently going to do the work, and if I make one or two small criticisms it is only in the hope of suggesting slight improvements that may not have occurred to him, and in the hope that he will be able to carry the apparatus to a still further stage where it may be useful to a larger number of people. The author states that a calibrated amplifier is not possible, but I do not agree, although the present type of amplifier is for certain reasons impossible. The first is that valves are not made as accurately as engineering products; manufacturers have not yet made a valve in which the conducting elements are as exact in size and in material as, for instance, in an optical instrument. It would then be necessary to take the characteristic curves for each valve, and to have on each valve an instrument to register the emission and the anode voltage, in order to bring each valve to a definite state during use. But the first thing to do is to produce valves which will not vary if they are shaken. The fundamental formula as given by the author, $D = 120\pi (Ih/d\lambda)$, has nothing to do with either the instrument or the measurement; it is merely a sort of basis for the comparison of transmission measurements. The author calls his coupling aperiodic, but this is surely not correct, because there is some capacity in the amplifier, and there is a coil connected to that capacity. It must therefore have a frequency, unless it is very highly damped. As regards screening, if a very strong signal is being measured the circuit of the local oscillator would pick up a small amount if it happened to be in the right orientation. In the calibration of thermo-ammeters by direct current, the only type of thermo-ammeter that can safely be used is a single-junction one; a multiple-junction ammeter will give very unexpected results. The reason is that the junctions are not absolutely symmetrical. The direct-current calibration of even the Duddell thermo-ammeter may differ very appreciably, e.g. 10 per cent, from that with alternating current at 300 periods or higher frequencies. It is greatly to be hoped that before long there will be a more continuous record of signal strengths, and also that it may be possible to get measurements on shorter waves. The formulæ of Fuller, Austin and one or two others give good results on comparatively long waves, say of 2 000 m and upwards, but if they were correct for short waves it would appear to be perfectly impossible for amateurs in London to hear 1 kW stations in America. There is very little doubt in my mind that these formulæ with their exponential coefficients do not cover waves down to 200 or 300 m, and it would be interesting to get some real measurements with short waves of considerable power. With short waves the consequent absence of disturbance from atmospherics would be of great advantage in the Tropics.

**Admiral of the Fleet Sir Henry Jackson:** In the absence of Prof. Howe, a member of the Radio Research Board, I will try to take his place and deal with the subject on their behalf. In the early days of the Radio Research Board we all came to the conclusion that some standard instrument was required for measuring the intensity of the fields at long distances from transmitting stations. Eventually the author agreed to take up the subject at the National Physical Laboratory, and this paper is the result of his work. We are, for the present, accepting the instrument as our standard, and I think that the tables shown justify us in saying that we want such an instrument. Four have been ordered: Prof. Howe is going to work one of them at Glasgow University; another one is going to Aberdeen University to be worked under Prof. MacDonald's auspices; one is going to Slough, and the fourth may be at Teddington, where one already exists at present. When these instruments are erected in the course of the next few months, we shall be able to see what difference there is between signals in the north and south of Scotland and in the south of England and possibly at some other places at the same instant. This will enable some idea to be gained as to whether the effects are local or whether they are really due to the Heaviside layer or any other cause. I hope also that it will be possible to co-ordinate direction-finding results with the measurement of these signals. It seems to me very important that if there are abnormally strong or weak signals, and the directional effects are peculiar, it would be worth while analysing the two together. With two stations, such as Slough and Teddington, in telephonic communication, we might be able to measure the two effects simultaneously and see if the bearing errors varied at the same time as the abnormal strength of signals on this instrument. The author mentions the fact that these electric waves may sometimes not arrive absolutely vertical on the antenna. In some work which I have been doing for the past two years I have tried to measure this inclination, if any, by means of a frame aerial which I can rotate in any plane. About a year ago I described some work which I had done with a frame aerial working on two axes, and I have now one which works on three axes. I have taken every precaution which has been suggested to me in discussions at the various Sub-Committees of the Radio Research Board, and I have obtained some interesting results. It is sometimes possible to put the axes at such angles that a rotation on one of them will not change the strength of the signal, and a blind band, a degree wide, will be obtained. The maximum deflection from the vertical that I have measured is about 20 degrees. I hope that others will carry out this sort of work and take measurements to observe if the waves are inclined. I have often noticed what may be called "wireless fogs." In one case at sunset I was observing a station and tuned to a 600 m wave, and I could get practically no directional effect at all for some minutes, but 20 minutes after sunset the bearing could be accurately measured. At other times the direction of near stations could be accurately taken, when distant stations gave no directional effect at all. These points may be of interest, and I hope that they will be considered in connection with the future measurement of signal strength.

**Dr. E. H. Rayner :** The work described has been carried out under very great disadvantages. The fact that only a few minutes a day have been available for making experiments, and never more than two minutes together, is sufficient to show what patience is required in work of this nature. It is to be hoped that there will be a considerable increase in the number of URSI signals and in their duration. Comments and suggestions will be most warmly welcomed by the Sub-Committee of the Radio Research Board which has to deal with this subject. The Committee make no claim for credit for the work which has been done by the author, and on their behalf, as Chairman of the Committee, it is a great pleasure to me to offer him their thanks and congratulations. The further work on these lines when we have a number of stations working, combined with simultaneous observations of the direction of the apparent wave-front, cannot fail to give results of the greatest value, especially on " disturbed " days.

**Mr. E. B. Moullin :** Every detail of this paper has been of peculiar interest to me, for the author and I have been working quite independently at the same problem during about the same period of time. I think that anyone who has used both the audible and the visual method of comparison, as both the author and I have done, must be convinced of the great superiority of the visual method. I think that, except in very special cases, the audible method is a thing of the past. The author's reference to the difficulty of adjusting to perfect resonance even in comparatively high-resistance circuits seems very familiar to me. I think that perhaps the difficulties in preparing the apparatus have made him slightly exaggerate the necessity of making measurements with great rapidity. Surely signal measurements are of great commercial importance, and if this is so the necessity merits plenty of special signals, and the serious experimentalist should not have to put up with the best that chance gives him. Large sums of money are being spent on erecting stations of ever-increasing power so as to ensure continuous service. This has proved a successful though expensive method, but now that signal measurements can be made with a visual indicator, with certainty and comparative ease I think that the solution of questions such as optimum wave-length for a given distance, the relation between wave-length and fading and wave-length and atmospherics, has become an economic necessity. If special signals are arranged during an interval of, rather than before, regular service three or four long dashes of half-minute duration should be ample ; the general disturbance caused thereby would be small. I am surprised that the author considers that reception with a loop is advisable, for it greatly enhances the difficulties. If an aerial is used, the E.M.F. set up by a given field strength will be vastly greater than that in a loop, and consequently the necessary number of amplification stages can be much reduced, with a great gain in ease of manipulation. It may be argued that the aerial has to be calibrated, but this can be done by measuring a strong signal both in the aerial and in a loop. Also, if signal measurements are required for investigating fading effects and the like, is it not relative rather than absolute values that are required ? I think that there is a good deal to be said for replacing the loop by a big aerial. Now if the E.M.F. to be measured is fairly large and the number of amplifier stages are few, I do not find that screening is a very difficult matter. As the author's method requires a local generator to calibrate the amplifier, is there not something to be said for introducing the local E.M.F. straight into the aerial circuit rather than working indirectly via the aerial resistance ? The author tells us that he does this to avoid screening, but if aerials are used instead of loops is there any point in avoiding screening ? With audible comparison I think there is, because, as the author says, there is always the uncomfortable feeling that perhaps the screening is not complete. With visual indication, on the other hand, this doubt need not exist. The current in the local generator being kept constant, the E.M.F. introduced into the aerial may be varied by altering the value of a mutual inductance or of a resistance potentiometer. If the screening is imperfect the E.M.F. introduced through stray paths will remain constant, while the E.M.F. that it is desired to introduce will vary. The galvanometer deflection can be plotted against the value of the mutual inductance, and if the result is a straight line through the origin, the screening is shown to be perfect. If it is not perfect then the screening can be improved until the calibration line does go through the origin. I have used this method of measurement * and find it to be comparatively simple. I should like to know the author's views in regard to the use of aerials and with regard to introducing the E.M.F. directly in the aerial. Does he consider that there is some distinct advantage in working via the aerial resistance ?

**Major H. P. T. Lefroy :** On page 505 the author lays emphasis on the necessity for using an accumulator for balancing, but he does not state what type of high-tension battery he employs. If it is an accumulator battery I can see his point, but if it is a dry-cell battery would he not get as good results by using, for balancing, one cell of the same type ? As the currents are balanced to zero, it follows that both batteries discharge at the same rate, and so the more uniform they are in construction the steadier should be the zero. On page 504 the author mentions that he has $\frac{1}{8}$ inch between the turns of his coil-aerial, but this apparently does not come into his calculations, unless it is covered by his measurement of the effective resistance of the coil aerial. I am doubtful whether, in the case of absolute measurements, it is safe to ignore the distance between the turns of such a coil aerial. It is my experience that, for a given area and number of turns, the wider the spacing of such turns the stronger are the signals received. I presume that this means that the voltage on the detector is greater the wider the spacing of the turns. It seems probable that the nearer the coil turns are, the more they tend to screen each other from the incoming signals. I am doubtful whether this effect is completely allowed for by measuring the effective resistance ; would it be just as good for the author's purpose to have, for instance, $\frac{1}{16}$ inch between turns ? On page 509 the author refers to the special conditions that existed on the 2nd February, 1922, and I should like to ask him whether he made a point of recording the meteorological conditions on that day ? From the nature of his investigations he is in a position to observe frequently the abnormal strength or weakness of standard signals, and a careful analysis of the corresponding meteorological reports might lead to some insight into what weather conditions accompany abnormal signal strengths. I have evolved a rough method for the measurement of signal strength, which may be described as a zero method. The receiver is first balanced to zero for silence ; when the signal arrives a certain deflection occurs ; by adjustment of the filament rheostat, whilst the signal continues, this deflection is again balanced to zero ; the rheostat is arranged to have an open scale and a suitable pointer, and the change in its value between the two positions of balance indicates roughly the strength of signal received. The change is usually about $\frac{1}{2}$ ohm to $\frac{3}{4}$ ohm, and the balances can be easily and rapidly obtained.

---

* See *Journal I.E.E.*, 1923, vol. 61, p. 67.

**Mr. T. L. Eckersley :** The value of the paper is enhanced perhaps because, it seems to me, the author has developed an instrument which differs in important respects from the ones that have been in use up to the present, i.e. the method due to Vallauri and that developed in the Marconi Company by Capt. Round, Mr. F. C. Lunnon, Mr. K. W. Tremellen and myself. A comparison between his apparatus and our own should give a valuable check on the accuracy of the overall working of each type of instrument. The chief novelty of the N.P.L. system is in the use of a galvanometer for matching the actual and local signal, and very strong opinions have been expressed during the discussion that this is the only reliable or even possible method, and, although I fully recognize the insensitivity of the aural method of matching signals, the galvanometer method has the serious disadvantage that it cannot be used on ordinary Morse signals. I should like to know whether the author has been able to measure with the galvanometer weak signals from the American stations, e.g. down to 4 or 5 microvolts per metre on wave-lengths between 10 and 20 km. With regard to the accuracy of matching audio signals I agree with the author that 5 per cent is about the limit of accuracy in normal working, but in exceptional cases where strong signals are used, interpolated by signals from the artificial circuit, an accuracy of 1 per cent has been obtained by Mr. Lunnon when comparing two signal-measuring instruments. I am inclined to feel that the gain in accuracy on using a galvanometer is outweighed by the disadvantage consequent on loss of audio selectivity and the impossibility of use on ordinary Morse signals. I should also be inclined to think that the galvanometer method would fail in the presence of strong X's where it is still possible to match audio signals with a fair degree of accuracy. The author's method also involves the measurement of the resistance of the receiving aerial. Personally I have always found this to be a difficult matter and one that is always liable to some uncertainty unless very special precautions are taken. Again, the mutual inductance must be measured. All these measurements—made against time—appear to me to introduce possibilities of error which the direct substitution method avoids. It has been our practice for some time past to do away entirely with the dummy circuit and induce the local signal direct into the aerial during the intervals of sending. The actual and local signals are then under the same conditions of X's and jamming, and can be matched without any fear of the psychological effects of X's marring the results. I can vouch for the fact that this method is possible, as I have received many thousands of observations from Mr. Tremellen taken in this manner on his voyage out to New Zealand. This method avoids all uncertainties of resistance measurements. It is sometimes difficult to find intervals to "chip in" when a station is sending high-speed automatic signals for long periods, but in this case it is possible to use a method devised by Mr. Beverage and Mr. Rust in which a unidirectional receiver is used, by combining vertical and aerial and frame, in which the intervals are artificially made by balancing the frame against the aerial. On page 503 it is not fair to say that if the wave be tilted the relation $I = 2\pi Dan/(R_2\lambda)$, where $D$ is the vertical force induced, holds, for the E.M.F. induced in this case also depends on the horizontal electric force $X$ in the direction of propagation and is $na \,.\, \partial X/\partial Z$. This quantity is, however, negligible in every case where the ground has not a greater resistivity than about 1 000 ohms per ft. cube, or about $2 \times 10^{13}$ units. With regard to the effect of jamming, it has been our experience, so far, that when using our types of measuring instruments, jamming makes very little if any effect on the measured strength of the signal received. The use of a strong local heterodyne makes the signal and the interference very approximately linearly independent, but I should doubt if this was the case when using ordinary rectification without heterodyne. This raises the point as to whether the absence of a local heterodyne is really an advantage. It certainly is an advantage in simplicity, but the point raised just now may be serious in certain cases, and ordinary square-law rectification makes weak signals difficult to measure. The author must be congratulated on being able to dispense with shielding, although his method of doing so is not exactly clear to me. It seems to me rather a dangerous proceeding, especially when dealing with very weak signals. The capacity coupling with a resistance-amplifier is likely to be of the same order of magnitude as the inductive coupling, so that the use of a resistance-capacity amplifier cannot facilitate to any great extent the problem of shielding. The fact that the local oscillator may be slightly mistuned without altering the effective E.M.F. induced in the amplifier seems to be a point in the favour of the N.P.L. system. With the use of a heterodyne very accurate setting of the local oscillator is necessary in order to match the heterodyne notes. This setting is often made more difficult by slight variations of the signal wave-length, and generally involves considerable care and time in adjustment.

**Mr. F. J. Chambers :** With reference to the need for a stable amplifier, I should like to ask the author if he has tried substituting well-insulated condensers for the grid-filament resistances. The reaction of the output circuits upon the input circuits, due to " valve " coupling, is then " counter feed back " and can be reduced to a negligible value by making the condensers large compared with the anode-grid capacity of the valve. The principal source of trouble in a resistance amplifier is the action at the first stage. This might be dealt with by connecting the source of E.M.F. to the first grid through a non-inductive resistance, with a further non-inductive resistance between the grid and filament of the first valve. If these resistances are properly chosen with reference to the other circuit constants, the anode reactance and the grid-anode capacity, I think that retro-action could be avoided.

**Mr. E. H. Shaughnessy :** On page 502 the author points out that the measurement of signals can be made either on the routine transmission or on a short, special signal sent for the purpose. He says: " Observations seem to show that the first of these is not of much value except for very rough measurement, owing to the continual and irregular variations produced by the keying." I should like to know precisely what he means by that; whether it is simply the fact that his galvanometer needle vibrates too much for him to get a reading, or whether the strength of the field when signals are coming in differs appreciably from that when a long dash is being sent. From a practical point of view we want to get signals and not long dashes. That is why up to the present the audibility method has been used for measurement, and, following the Marconi practice, we have always applied it to actual signals. The table on page 509 shows that the strength of the field as measured varies from 1 040 on 20th November to 2 250 on 17th November and 1 900 on 21st November. I am ignoring the abnormal figures, and I presume that these measurements were taken at the same time every day. An engineer designing a station is very badly in need of some substantial and accurate figures of this nature. The strength of the signals on one day was 4 260, and someone may accept this as reliable, whereas the figure that should be taken is that for 8th January, viz. 840. Measurements taken all over the world with apparatus of this or a similar nature will be very valuable to us all.

**Professor E. W. Marchant** (*communicated*) : In a paper read before the Institution in February, 1915, (see *Journal I.E.E.*, vol. 53, p. 329) I described a method of measuring the signal strength which had been used in the Liverpool Laboratories of Applied Electricity for determining the variation in the strength of the Paris time signals and of a station at Brussels. In these tests we used an Einthoven galvanometer in conjunction with a crystal (perikon) detector which was calibrated by a buzzer circuit, the current being measured by a Duddell thermo-ammeter. These measurements were mainly relative, the absolute values of the microvolts per metre on the aerial not being estimated. The aerial was very badly placed for this purpose as it was attached to a mast erected on the top of a steel-frame building, and its effective height, therefore, would be difficult to determine with any degree of certainty. Since last September, Mr. Sharpe in this laboratory has been constructing an apparatus for measuring signal strengths of much longer wave-length, the arrangement used being somewhat similar to that described by Mr. Lunnon in the discussion some two years ago on Mr. Elwell's paper on " Long-Distance Wireless Transmission." * The arrangement described in the present paper, also, is somewhat similar to our system, the galvanometer being connected in the plate circuit of the last valve, a balance current, obtained from a secondary cell, compensating for the steady current which flows through the plate circuit, so that the galvanometer only records variations in the plate current, corresponding to the received signals. So far, no actual measurements have been obtained of the long-distant stations. The greatest difficulty in connection with these tests has been the elimination of signals of similar wave-length to those being measured. The method of calibrating the detector described by the author is very similar to that which we used in our tests in 1914, but the variations in signal strength that the author has obtained and described on page 509 are much greater than those found in most of our experiments for the daytime. The actual variation during the day for the Paris time signals in Liverpool (which would be roughly the same distance as Nantes is from the N.P.L.) is of the average order of ± 25 per cent, depending on weather conditions. Variations during the night are, of course, very much greater and I presume that the figures given on page 509 for the signals from Nantes (UA) must include some measurements after dark. The variation in the effective resistance of his testing set appears to be very considerable, having a minimum value of 6·3 and a maximum of over 42. It is difficult to understand exactly why it is necessary for the receiving set to have such a very wide variation of effective resistance. Would it not be better to use for receiving a set in which the effective resistance was practically constant? Reference is made on page 508 to the variation in sensibility of the author's receiver with varying high-frequency E.M.F. of the received signal. Unless one is going definitely beyond the saturation point of the valve with any of the signals, there should not be any serious change of sensitivity with varying E.M.F. of the received signal. It is, I think, desirable to work the amplifying valve as near as possible to the centre of the straight part of the characteristic curve, so as to make sure that this condition does not occur.

**Mr. J. E. Taylor** (*communicated*) : Some 11 or 12 years ago I had some preliminary tests made with a view to measurements of wave-strengths at a distance from the transmitting station. At that date damped-wave transmission from spark transmitters was in general use and the tests were confined to such transmission and to relatively short waves not far removed from the natural wave-length of the aerial used and of perhaps 200 m to 400 m. The distance from the transmitting station at which the measurements were made was also quite small, i.e. about two or three miles. The method consisted of inserting a Duddell thermo-galvanometer into a receiving aerial, and an attempt was made to obtain a resonance curve from the galvanometer readings while varying the tuning of the receiver through a suitable range. It had been expected that the curve so obtained would bear some direct relation to the resonance curves obtained at the transmitting station by the usual method of wave-meter and thermo-milliammeter. On the contrary, however, the curves at the receiving station had entirely different characteristics and indicated a bluntness of tuning not accountable for by the measured effective resistance of the receiving system. They also exhibited a double-hump characteristic in which the humps bore no sort of relation to the coupling waves of the transmitter. The bluntness of tuning was such as to swamp entirely any characteristics of the transmitter, the coupling waves of which might be varied within wide limits without being detectable. It was also confirmed that with ordinary wireless crystal receivers the coupling waves were undetectable, so that the necessity for legislation as regarded the permissible limits of coupling of transmitters was not obvious. Such legislation appears to have been based on erroneous assumptions derived from resonance curves taken at the transmitting station itself. Probably somewhat similar tests have been since carried out by other investigators and have been carried to a more definite conclusion than the incomplete series to which I refer. Bearing in mind the nature of the results obtained with damped-wave transmission as above, I should like to know if the author has evolved any resonance curves with his apparatus on continuous-wave reception and, if so, whether he has found that they bear any direct relation to resonance curves obtained at the transmitting station. If he has not yet made such tests I think it would be time well spent to do so. The author's method, systematically pursued, promises results of great interest, more especially in regard to comparative results as between different types and locations of stations, as well as seasonal and other variations of signal strength.

---

* *Journal I.E.E.*, 1921, vol. 59, p. 677.

**Mr. J. Hollingworth** (*in reply*): I quite agree with Dr. Erskine-Murray that the problem of a calibrated amplifier is one of apparatus rather than of principle, and it is quite likely that with improvements in valve construction such a thing will become possible, though it seems likely that even then the adjustments might be highly critical. In accordance with his suggestions the word "aperiodic" has been changed to "untuned." As to "pick-up" in the local oscillator, if it were suspected, it could be eliminated by slightly changing the wave-length, as it has been shown that such small changes do not affect the calibration. There is no doubt a great field in the extension of such measurements to short waves and it is hoped to carry it out, but with the reduction in wave-length the instrumental difficulties increase very rapidly owing to the increased effect of small stray capacities at the higher frequencies.

It is hoped that further tests may justify the use of the apparatus as a standard as suggested by Admiral Sir Henry Jackson, but on work of this nature it is important to define what is meant by this expression. In ordinary electrical measurements no instrument can lay claim to be called a standard unless it can be relied on to an accuracy of at least one in a thousand. In the present state of radio work of this nature such an achievement is, of course, impossible; and the word must be taken as implying that the limits of accuracy are definitely defined in each case. The check involved by the resistance measurement appears to provide this, and gives a power of separating good and bad readings whether such are due to the set itself or to transmission irregularities. During the Horsea tests last year some experiments were made to see if there was any direct connection between abnormal bearings and abnormal signal strength. The results, considering individual observations, appeared to be entirely negative, but from results such as that on 2nd November it appears that a period of abnormal signal strength may be accompanied by directional variations, even if the converse is not true. When the station at Slough starts working regularly such simultaneous observations would be possible and certainly of value.

The problem of aerial versus coil raised by Mr. Moullin is one in which there is a great deal to be said on both sides. The fundamental advantage of the aerial is certainly the large E.M.F. and, consequently, the decreased amplification involved. The primary reasons for the use of a coil in these experiments were portability and possibility of use in places where an aerial was impracticable; also the coil has the advantage that its constants are much more definitely known than those of an aerial. For pure comparative purposes this does not matter, but it affects any attempt to obtain absolute figures. The determination of the effective height of an aerial is one on which there is much uncertainty at the present,* and Vallauri has shown † that it may vary very considerably with the orientation of the observing station. It also varies with the wave-length, and possibly with the surface conductivity of the ground in the neighbourhood. The method of injecting the calibrating E.M.F. into the aerial is practically that of Lieut. Guierre and is discussed on page 502 of the paper, the whole problem being the difficulty of ensuring a silence period in which to perform the injection.

In reply to Major Lefroy the high-tension battery consists of small Leclanché wet cells. So far this has given no trouble, though admittedly it is fairly new. The steadiness of the anode current (i.e. the filament emission) depends on two factors, the anode voltage and the filament temperature. If the valve be run very bright on the upper flat portion of the temperature/emission characteristic, the latter of these two factors is negligible and the problem is merely a question of steadiness of anode voltage. For efficient working it is usual to run the filament less bright on the steep part of the characteristic, and in this case a much greater variation of anode current is caused by small variations of filament voltage than by corresponding small variations of anode voltage. In this case it has been found best to balance the filament drop by an accumulator working on a potentiometer of about the same resistance as the filament.

---

* Eckersley: *Electrician*, 1923, vol. 90, p. 134.
† *Radio Review*, 1921, vol. 2, p. 186.

The question of spacing is a very interesting one. It is equivalent to the consideration of the screening effect of the current in any turn on adjacent turns. Now the occurrence of such an effect is illustrated by the fact that if the wire resistance of a coil were decreased indefinitely the current in it would tend to a finite limit. This is shown in the theoretical treatment of the coil by the appearance of a quantity known as the radiation resistance, which depends on the dimensions of the coil and is added to the normal wire resistance. It appears, therefore, that any such effect is allowed for by the measurement of the resistance under working conditions. Actually the radiation resistance of a coil is usually very small compared with its wire resistance. A more likely reason for the effect referred to by Major Lefroy is that as the spacing between the turns is decreased the inductance rises fairly rapidly. Now I have mentioned on page 505 that if there be any power absorption by the valve, or loss due to poor insulation resistance, the effective resistance due to this is nearly proportional to the square of the inductance. It seems more likely that the behaviour referred to was due to this cause than to the one previously discussed. There is also the fact that the actual high-frequency resistance of the wire composing the coil itself is affected by the spacing. I think that there is no doubt that the meteorological conditions play a considerable part in the variations, although I have not actually confirmed it in the case of 2nd November, but it is an effect I have frequently suspected from the results obtained. It will certainly be taken into consideration as soon as systematic observations begin. As to the earlier remarks of Mr. Eckersley, I agree that it is too early to give a definite decision as to the relative values of galvanometer and telephone methods, though there appears to be a general tendency among the more recent workers to use the galvanometer. Personally I am inclined to think that, owing to the large number of different conditions under which such measurements are required, there is room for both types.

One object of signal strength measurements, and indeed a very important one, is the determination of their value under actual routine conditions of working. These are not invalidated by such factors as excessively weak signals, bad atmospherics and unsteady transmission, which factors must be allowed for in considering such transmissions, and even if the results obtained are not of a very high order of accuracy their value is considerable. For such work an audibility measurement is probably most suitable. The N.P.L. apparatus was, on the other hand, designed more for theoretical observations on the "URSI" signals. In this case the limits of accuracy of each individual observation must be known and must be correlated with carefully observed sending conditions. Observations on the dashes seem to suggest that a transmitting set does not always settle down immediately to a steady condition when the key is pressed, and in this case it is not easy to specify the exact transmitting conditions when Morse signals are being sent. This also covers the point raised by Mr. Shaughnessy. The consistency of the resistance series obtained seems to show that, for a coil at any rate, it is a fairly definite quantity, though with an aerial it might not be so. The mutual inductance has not to be measured during the observation, as it is determined once and for all during the preliminary calibration of the apparatus. This and the fact that accurate tuning of the local oscillator is unnecessary make the actual measurement very rapid. Readings have been obtained with time to spare in cases when no preliminary signals were sent, but merely the URSI call immediately followed by the dash. I think that the abolition of the dummy aerial in Mr. Eckersley's system is a very great improvement, though it is only obtained rather at the expense of simplicity of apparatus. I do not quite follow his remarks as to capacity coupling, as he does not say between what points he is considering it; the primary reason for there being no need of screening is that the coil and local oscillator are never working at the same time. The capacity component of the calibrated mutual inductance is allowed for by the method of calibration, and stray capacities between the oscillator and amplifier are minimized by mounting everything on porcelain legs. It was found by experiment that the ratios of the mutual inductances of the various secondary coils as measured by the method given in Fig. 3 agreed generally within 1 per cent with the same ratios obtained by varying the current in the calibrated oscillator so as to give the same galvanometer deflection on the amplifier with different pairs of secondary coils. As the amplifier is not used at all in the first method this shows that the effect of such stray capacities is negligible.

I have not tried the method suggested by Mr. Chambers, but any method of controlling rather than abolishing retro-action is to be welcomed.

The variations in resistance referred to by Prof. Marchant are due to three causes. The first, which in general accounts for the slight variations, is due to slight changes in the batteries, etc., and also at times to dust or damp on the leaks. The amplifier used for these measurements was the original model constructed in the early days of the experiments. Many modifications and improvements are being incorporated in the later model which is now under construction. The two other causes were intentional. The first of these was that the amplifier adjustments were varied so as always to give a practically full-scale deflection on the galvanometer. For instance, in a case where the signal was larger than usual and the galvanometer under normal conditions just off the scale it gave a finer adjustment to vary the amplifier slightly than to use the galvanometer shunt of which successive steps were in the ratio 3 : 1. The extreme variations were due to another cause. As in this method of measurement the state of the amplifier is directly involved in the calculations, it was thought to be of the utmost importance to show that this did not affect the final result. The amplifier was therefore varied by using two, three or five valves and widely varying amplifications on different occasions. This is strongly illustrated in the reading on Rome on 5th January where the amplifier was deliberately made almost reactive, its resistance being only 1·7 ohms; and yet the reading was still consistent with others, whereas the amplification was many times greater. The readings on Nantes were all taken at 2.15 p.m. (G.M.T.), this being the time of the special signal. The variations are certainly large, but appear in general to be of the same order as those observed at Meudon on similar transmissions.

In reply to Mr. Taylor I have not been able to determine any resonance curves such as he refers to, but this could easily be done when the transmission from Teddington to Slough is in working order.

# PERMISSIBLE CURRENT LOADING OF BRITISH STANDARD IMPREGNATED PAPER-INSULATED ELECTRIC CABLES.

## SECOND REPORT* ON THE RESEARCH ON THE HEATING OF BURIED CABLES.

[Report of the British Electrical and Allied Industries Research Association, presented by Mr. S. W. Melsom (National Physical Laboratory), Associate Member, and Mr. E. Fawssett, Member.]

(*Read before* The Institution *1st March, before the* North-Eastern Centre *12th March, before the* North Midland Centre *20th March, before the* North-Western Centre *20th March, and before the* South Midland Centre *4th April,* 1923.)

### Contents.

Page
Synopsis .. 518
List of symbols .. 521
Explanatory notes to current-loading tables .. 521

Current-loading tables:

*Cables laid direct in the ground.*

660-volt single-core .. 524
660-volt concentric .. 525
660-volt three-core .. 525
2 200-volt concentric .. 525
2 200-volt three-core .. 526
3 300-volt concentric .. 526
3 300-volt three-core .. 527
5 500-volt concentric .. 527
5 500-volt three-core .. 528
6 600-volt concentric .. 528
6 600-volt three-core .. 529
11 000-volt concentric .. 529
11 000-volt three-core .. 530

*Cables in air.*

660-volt single-core .. 530
660-volt concentric .. 530
660-volt three-core .. 530
2 200-volt concentric .. 531
2 200-volt three-core .. 531
3 300-volt concentric .. 531
3 300-volt three-core .. 531
5 500-volt concentric .. 531
5 500-volt three-core .. 531
6 600-volt concentric .. 531
6 600-volt three-core .. 531
11 000-volt concentric .. 532
11 000-volt three-core .. 532

*Cables drawn into ducts.*

660-volt single-core .. 532
660-volt concentric .. 532
660-volt three-core .. 532
2 200-volt concentric .. 532
2 200-volt three-core .. 532
3 300-volt concentric .. 532
3 300-volt three-core .. 532
5 500-volt concentric .. 533
5 500-volt three-core .. 533
6 600-volt concentric .. 533
6 600-volt three-core .. 533
11 000-volt concentric .. 533
11 000-volt three-core .. 533

Theoretical and experimental work:

(1) Power losses in the cable .. 533
(2) Thermal constants of impregnated paper dielectric .. 534

Theoretical and experimental work—*continued.*

(3) Thermal constants of the surrounding soil:

Page
(*a*) Thermal resistivity .. 535
(*b*) Moisture content .. 537
(*c*) Depth of laying .. 538
(4) Temperature of the ground .. 538
(5) Expansion of cables .. 538
(6) Maximum permissible temperature for paper-insulated cables for pressures up to and including 11 000 volts .. 541
(7) Summary of proposed British constants and those adopted by other countries .. 541
(8) Representation by general formula .. 542
(9) Current-rating of three-core cables used on three-wire circuits .. 545
(10) Current-rating of four-core cables .. 546
(11) Current-rating of triple-concentric cables .. 546
(12) Cables for pressures above 11 000 volts .. 546
(13) Comparison between heating of three-core cables with three-phase current and direct current .. 546
(14) Grouped cables laid direct in the ground .. 547
(15) Current-rating of cables in air .. 551
(16) Correlation of results with cables in air and when laid direct in the ground (and drawn into ducts) .. 551
(17) Current-rating of cables drawn into ducts .. 552
(18) Grouped cables drawn into ducts .. 552
(19) Time required for cables to attain maximum temperature .. 553
(20) Current-rating of cables for cyclical intermittent loading .. 554
(21) Current-rating of cables for emergency loading 560
(22) Work still outstanding .. 561
(23) Acknowledgment .. 561

Appendix I: Particulars of the cables employed in the investigations .. 562
Appendix II: Examination of Mie's formulæ by Mr. S Butterworth .. 565
Appendix III: Experimental determination of thermal resistance by means of an electrostatic analogy .. 566
Appendix IV: Calculation of the thermal resistivity of three-core cables, and examination of Russell's formula by Mr. E. B. Wedmore .. 568
Appendix V: Moisture content of the soil in the Newcastle-upon-Tyne district .. 570
Appendix VI: Determination of the emissivity of lead sheaths by Mr. J. F. Watson .. 570
Appendix VII: Determination of thermal resistance of multi-core cables with segmental conductors .. 572
Appendix VIII: Thermal resistivity of chalk soil .. 574
Appendix IX: Graphical representation of selected load tables .. 574
Bibliography .. 578

---

* See *Journal I.E.E.*, 1921, vol. 59, p. 181.

### Synopsis.

This Report describes the further investigations on the Heating of Buried Cables and includes the essential portions of the Preliminary Report (*Journal I.E.E.*, 1921, vol. 59, p. 181).

The theoretical and experimental work has been carried to a stage at which it is possible to issue tables of maximum permissible currents for all the sizes and types in general use of paper-insulated cables dealt with in the British Standard Specification for Dimensions of Insulated Annealed Copper Conductors for Electric Power and Light (B.S.S. No. 7—1922).

*Tables of maximum permissible currents* (page 521).—Tables of maximum permissible currents for all the sizes and types in general use of impregnated-paper lead-covered cables dealt with in B.S.S. No. 7—1922, have been calculated on the basis of experimental results obtained with a large series of cables, both with circular and segmental conductors and including both armoured cables laid direct in the ground and lead-covered cables in ducts.

Full notes are given with the tables, explaining the method and bases of calculation, and an indication of the effects of variations from the assumed constants.

*Constants employed* (page 534).—The constants recommended and on which these tables are based are as follows, the reasons for making this selection being given later :—

(1) Thermal resistivity of the dielectric (page 534) :
For cables up to and including 2 200 volts = 750.
For cables above 2 200 up to and including 11 000 volts = 550.

Higher values have been adopted for cables with conductors having sectional areas less than 0·06 sq. in. to allow for the difficulty in manufacturing small cables.

(2) Thermal resistivity of armouring and protective coverings (page 524) = 300.
(3) Thermal resistivity of the soil (page 535).

Current-loading tables are given corresponding to the following values of thermal resistivity and moisture content :—

| Thermal Resistivity, $g$ | Approximate Moisture Content | |
|---|---|---|
| | Sandy Loam | Heavy Clay |
| 340 | 0 | 1 % |
| 180 | 5 % | 17 % |
| 120 | 10 % | — |
| 90 | 15 % | — |

In the case of heavy clay soil with moisture content greater than that given above the value of the thermal resistivity is not reduced appreciably ; for instance, with a moisture content of 25 per cent the thermal resistivity is approximately 150 (see Fig. 5).

(4) Depth of laying (page 538).

As representing average practice the depth of laying is taken as 18 in. to the cable axis for cables for pressures up to and including 2 200 volts, and 3 ft. for cables for pressures above 2 200 volts up to and including 11 000 volts.

(5) Temperature limits (page 541).

The normal maximum temperature of the soil is taken as 15° C.

The maximum temperature to which the dielectric and conductor may be exposed is taken as 65° C. for armoured cables laid direct in the ground, and 50° C. for plain lead-sheathed cables drawn into ducts.

The temperature-rises on which the tables are based are therefore 50 degrees C. and 35 degrees C. respectively.

*Theoretical and experimental work* (page 533).—The report and appendixes together give a detailed account of the problems underlying the investigation and the experimental work necessary for their elucidation. These may be briefly summarized here.

The evaluation of the temperature-rise of the conductor of a cable buried in the ground depends on the fundamental relation

$$H = t/(S + G)$$

where $H$ = heat developed in the conductor per sec.
$t$ = temperature-rise of the conductor.
$S$ = thermal resistance between the conductor and the surface of the cable.
$G$ = thermal resistance of the ground surrounding the cable.

The consideration in detail of the separate terms of this equation is a convenient way of reviewing the main outlines of the problem.

The heat per sec. $H$ depends on the current and the resistance of the conductor or conductors. In the report it is expressed in watts. The introduction of any conversion factor in the equation is thus obviated, as the thermal resistances and resistivities are also expressed in electrical measure (i.e. the difference in degrees C. which causes the transference of one watt, or one joule per second, of heat).

The dielectric loss is neglected as it is negligible within the limits of 65° C. and 11 000 volts.

The temperature-rise $t$ of the conductor is an arbitrary value which has been adopted as the result of existing data.

Existing information as to the temperature to which cables can be subjected for long continued periods without injury is most conflicting, and the experimental work necessary to provide reliable values is not complete and will necessarily require a considerable time. All published results have been fully examined, as have also other factors such as the expansion and consequent mechanical strains on cables subjected to alternate heating and cooling, and after full consideration of all sides of the question, including the reliability expected with underground mains, values of a maximum permissible conductor temperature of 65° C. for armoured cables laid direct in the ground, and 50° C. for plain lead-sheathed cables drawn into ducts were adopted.

A large amount of data has been collected for Great Britain and other countries, including India and Australia, of the temperature of the ground at various depths. The information is given in the form of curves showing the values for a complete year. Taking the abnormally hot years of 1911 and 1921, the ground temperature in Britain from November to April is below 10° C., and it only exceeded 15° C. during the months of June, July and August. The value of 15° C. adopted by the Association for the normal maximum ground temperature for Great Britain, therefore, is well above the actual mean value and is only exceeded during the period when the cables are likely to be lightly loaded.

The thermal resistance $S$ of the cable, which is expressed in electrical measure per unit length of cable, depends on two factors :—

(*a*) The thermal resistivity of the dielectric.
(*b*) The lines of heat-flow from the conductor to the surface of the cable.

Regarding the dielectric, initial values given in the Preliminary Report (*Journal I.E.E.*, 1921, vol. 59, p. 181) showed variations of the order of from 400 to 1 200 in the value of the thermal constant $K$ for cables made with apparently similar material. Further tests have therefore been made with modern cables, and as a result of these and of an investigation of the method of calculation, the values given on page 535 are recommended.

Since it is necessary to determine the thermal resistance of any size or type of cable from a knowledge of the thermal resistivity of the material, the lines of heat-flow through the dielectric and the extent to which they affect the value of thermal resistance are of primary importance. In the cases of single-core and concentric cables the problem is simple, but for multicore cables the lines of heat-flow are complicated, and comparison of three existing formulæ due to Russell and to Mie made it clear that none of them was completely satisfactory.

Experimental determinations were therefore made, and it was found that considerable corrections were required. Russell's formula on account of its greater simplicity has been mainly used with the corrections evolved as a result of experiment. A curve of the errors for different sizes of cables is shown in Fig. 36. The errors range from 10 per cent for a cable as used for 20 000 volts to over 30 per cent for a 660-volt cable.

The thermal resistivity of the armouring and protective coverings taken as a whole has been determined for a number of cables and the value taken is based on these experimental determinations.

*The thermal resistance $G$ of the soil* (page 535).—Here again two factors are involved.

(*a*) The thermal resistivity of the soil.
(*b*) The lines of heat-flow from the cable.

The thermal resistivity of the soil depends largely upon the amount of moisture present, and partly upon the type of soil. A full series of tests was made with both sandy loam and heavy clay, in order to determine the effect of varying moisture contents. Curves giving the values obtained are shown in Fig. 5. Sandy loam with a moisture content of 5 per cent has a thermal resistivity of 180, as compared with 90 for the same soil with 15 per cent of moisture. With heavy clay having about 17 per cent moisture—nearly the normal value for such soil—the value is 180.

As an example, a particular three-core 0·1 sq. in. 6 600-volt cable laid direct in the ground at a depth of 3 ft. would have a current rating of 228 amperes for a thermal resistivity of 90, and 192 amperes for a thermal resistivity of 180; the effect, however, varies with different sizes and types of cables, as may be seen by reference to the tables (see pages 524–533).

A large amount of data has been collected from various parts of the country, and in one case from abroad, giving the actual amount of moisture present in the soil at different periods of the year and under various climatic conditions. As a result it appeared that a fair average would be 10 per cent for sandy loam and 20 per cent for clay soil; but in view of the large differences possible, and especially in view of the opinion expressed that in some cases the soil around a continuously loaded cable becomes quite dry, it was decided to draw up load tables for four values of thermal resistivity corresponding to moisture contents ranging from 0 to 15 per cent for sandy loam, and 1 to about 20 per cent for heavy clay.

The appearance of soil is not a safe guide to its moisture content, as soil that is apparently quite dry is likely to contain 5 per cent of moisture.

The exact nature of the process of heat transmission through the soil has been the subject of much discussion, and various assumptions have been made regarding it. Kennelly in America and Teichmüller in Germany adopted a formula based on the assumption that the surface of the ground above the cable was an isothermal, which implies that all the heat was ultimately transmitted to the surface of the ground, which being in contact with free air remains at uniform temperature. An alternative was the assumption of Apt that the cable was surrounded by a series of concentric isothermals, which implies that the heat-flow proceeds uniformly in all directions. The assumptions of Kennelly and Teichmüller, although widely accepted, are not strictly accurate and the subject required data based on actual experiment. Special tests, in which all the usual variables were excluded, were therefore made to determine the shape of the isothermals of heat-flow under ideal conditions, and it was found that neither of the above assumptions was correct (see page 543). Further, a large number of tests have been made on cables of different sizes laid direct in the ground, and from these results, corrected to a common basis, in conjunction with the information obtained above on heat-flow the Kennelly formula was modified so that it more nearly fits the facts, and it is on this new basis that the current tables now submitted have been calculated.

*Depth of laying* (page 538).—The effect on the heating of a cable due to variation in the depth of laying can be calculated by an adaptation of the formula mentioned above. Experiments were made with three lengths of cable laid at different depths, and the results obtained are in fair agreement with those calculated. In the specific case of a cable laid at various depths, the proportional values of the currents required to produce a given temperature-rise where all conditions were equal were 100, 97 and 92, at depths of 1 ft. 6 in., 2 ft. 6 in. and 4 ft. 6 in. respectively. This, however, must not be taken as a safe general rule, since it is likely that for a considerable part of the year the moisture content at a depth of 1 ft. 6 in. would be less than at 4 ft. 6 in., and that the ground temperature would be higher.

*Other factors affecting the rating.*

(*a*) Grouped cables laid direct in the ground (page 547).—The extent to which the rating of a cable is affected by the proximity of other cables has been investigated both theoretically and experimentally, and a method has been developed for the predetermination of the mutual effect of two or more cables. Practice as to conditions of laying varies enormously and no general rule can be given. The method must, therefore, be applied in each particular case. As an example, however, for two cables laid in the same horizontal plane in a trench the maximum permissible current would have to be reduced in the ratios shown in the following table (see Table 37) :

| Distance between Axes of Cables in Inches | Ratio of Maximum Permissible Currents for Two Cables |
|---|---|
| 4 | 0·76 |
| 8 | 0·82 |
| 12 | 0·86 |

At a distance apart of from 4 ft. to 6 ft. the difference becomes almost inappreciable.

Where two cables are laid in the same trench and in the same vertical plane with 5 in. between the axes the ratios would be approximately as follows :—

With the uppermost cable 1 ft. 6 in. below the surface.

| | |
|---|---|
| For a small cable .. .. | 0·86 |
| For a large cable .. .. | 0·78 |

With the uppermost cable 3 ft. below the surface.

| | |
|---|---|
| For a small cable .. .. | 0·83 |
| For a large cable .. .. | 0·75 |

(*b*) Cables drawn into ducts (page 552).—The existing information available for cables drawn into ducts is meagre and not capable of general application. Moreover, in view of the lagging effect around the cable due to the air which may or may not be in motion, it appeared to be improbable that a general simple rule could be devised. Experiments were therefore made to determine the difference in the rating of cables of various sizes under the following conditions :

(i) When in air free from draughts.
(ii) When drawn into a duct.

The first depends entirely on the constants of the cable, so that comparison of the two sets of values should indicate the effect of the duct. The tests made showed that with all sizes of cable from 0·1 sq. in. concentric (external diameter = 1·1 in.) to 0·5 sq. in. concentric (external diameter = 2·1 in.) and 0·15 sq. in. three-core armoured (external diameter = 2·9 in.) the factor connecting the values of current for an equivalent rise of temperature in air varied from 0·98 to 0·935, the lower value being due probably to the armouring, which gave a somewhat different value in air. This made it clear that the greater part of the resistance to the flow of heat from the cable was in the thin layer of air immediately around the latter and that the relative size of cable and duct made little difference to the final result. It was decided, therefore, that current-loading tables for one plain lead-sheathed cable in a duct should be drawn up on the basis that the current required to produce the same temperature-rise in a cable in a duct is 0·95 of that for the same cable in air free from draughts.

(*c*) Grouped cables drawn into ducts (page 552).—Some tests have been made with the six-way duct shown in Fig. 20 in order to determine the effect of grouping, but these are not sufficient to allow of general application. Further experimental work is required on this subject.

*Current-rating of cables in air* (page 551).—All the cables used in the investigations have been tested in air free from draughts. Tests under this condition provide a satisfactory basis from which the behaviour under other conditions can be deduced in the light of the information now available as to the effect of laying direct in the ground or drawing into ducts. A formula has been developed which fits the experimental series very well, and the current-loading tables for cables drawn into ducts have been based on this. The values for the air conditions depend on the emissivity constant of the surface of the cable, among other factors. This constant varies with the nature of the surface, but there is not a great and consistent difference between the black surface of an armoured cable and a plain lead sheath. In cases when the lead sheath is new and bright the value is distinctly lower, but in general the values for both are of the same order, and it seems probable that when the surface of the lead has become dull the emissivity constant is substantially the same as for a black surface.

*Current-rating of cables for cyclical intermittent loading* (page 554).—It was suggested in the discussion on the Preliminary Report that use might be made of the thermal time-constant of a cable for the calculation of the short-time rating, but it was found that the method was not applicable, since a cable buried in the ground behaves essentially differently from one in air. In order to meet the case experiments were made with cables loaded in accordance with information given by electric supply authorities. In general the increase of current loading for intermittent load conditions is not large, varying from 3 per cent to 10 per cent, which amount was thought to be insufficient to justify a recommendation for increased rating for intermittent loading.

*Current-rating of cables for emergency loading* (page 560).—Two of the types of short-time cyclic loading referred to above were also designed to give information on which to base a rating for one or two hours only, for use in emergency.

These figures show considerable increases over the maximum continuous permissible currents without exceeding the specified maximum temperature, and are more nearly independent of the method of laying. On the score of damage to the dielectric this temperature might be exceeded on emergency, but the same limit is retained to obviate damage due to abnormal expansion, especially differential expansion between conductor and lead.

As an example, a 0·15 sq. in., three-core, lead-covered and armoured cable as used for 20 000 volts laid direct in the ground, if running continuously at half its rated current, will thereafter carry for one hour 20 per cent or for two hours 13 per cent over and above the maximum continuous rating. In general, larger cables will carry a greater, and smaller cables a less, increment than the above.

*Comparison between the heating of three-core cable with three-phase current and direct current* (page 546).—Experiments were made to determine whether there was any appreciable increase of heating of a three-core armoured cable when loaded with three-phase alternating current as compared with that observed with an equal direct current. Tests were made with a 0·15 sq. in., three-core cable, lead-covered and wire armoured, at frequencies of 25 cycles and 50 cycles respectively. No measurable difference between these results and those obtained with direct current was found, and it seems clear that for a cable of this size the skin effect and eddy currents in the sheath do not produce any appreciable additional heating effect.

*Work outstanding.*—A statement is given of the work necessary to complete the investigation, dealing more particularly with cables for pressures above 11 000 volts.

### LIST OF SYMBOLS.

The symbols generally adopted throughout the report are given below, all dimensions being in centimetres. They include all except a few which have been used incidentally and of which the meanings are explained in the body of the report as they occur.

$a$ = distance of the axis of the conductor from the cable axis in a multi-core cable.

$b$ = maximum distance between conductor and cable axis in three-core cables with segmental conductors.

$c$ = minimum distance between conductor and cable axis in three-core cables with segmental conductors.

$D$ = thickness of dielectric between conductors and between any conductor and lead sheath of three-core cables, centre point not earthed.

$E$ = thickness of dielectric between any conductor and lead sheath of three-core cables, centre point earthed.

$G$ = thermal resistance per cm length of cable between outer covering or sheath of the cable and surface of the ground in electrical measure.

$g$ = thermal resistivity of the soil surrounding the cable expressed in the same units as $K$.

$H$ = heat in watts developed in a cm length of each conductor.

$h$ = emissivity constant, i.e. watts per degree C for 1 sq. cm.

$I$ = current in each conductor.

$K$ = thermal resistivity of dielectric in electrical measure, i.e. as a difference in degrees C. between opposite faces of a cm cube, to cause the transference of 1 watt of heat.

$K_1$ = thermal resistivity (mean) of protective coverings of cable.

$L$ = depth of cable axis below the surface of the ground.

$n$ = number of separate conductors.

$R$ = resistance per cm length of each conductor at 15·6° C.

$R_1$ = resistance per cm length of each conductor at the temperature of operation.

$r$ = radius of the conductor of a multicore cable.

$r_1$ = radius of the conductor in a single-core cable or of the inner conductor in a concentric cable.

$r_2$ = inner radius of the outer conductor of a concentric cable.

$r_3$ = outer radius of the outer conductor of a concentric cable.

$r_4$ = inner radius of the lead sheath.

$r_5$ = outer radius of the lead sheath.

$r_6$ = external radius of the outer covering of finished cable.

$S$ = thermal resistance per cm length of cable between conductor and outer covering or sheath in electrical measure.

$t$ or $t_1$ = temperature-rise of the conductor in degrees C.

$t_2$ = temperature-rise of the sheath in degrees C.

$t_3$ = temperature-rise of the outer conductor of a concentric cable in degrees C.

### TABLES OF MAXIMUM PERMISSIBLE CURRENTS (CONTINUOUS LOADING) FOR IMPREGNATED PAPER-INSULATED CABLES, TOGETHER WITH NOTES GIVING THE BASIS AND METHOD OF CALCULATION.

The current-loading Tables, 3 to 27 inclusive, refer to the following types of cable and methods of laying :—

(i) Armoured cables laid direct in the ground.
(ii) Armoured and unarmoured cables in air.
(iii) Unarmoured cables drawn into ducts.

The arrangement of the current-loading tables corresponds to that adopted in B.S.S. No. 7—1922, and the numbers of the Tables in that Specification have been added for convenience. Cross-sections of three-core cables are shown in Figs. 1 and 2.

### EXPLANATORY NOTES.

*General.*—The fundamental relation connecting the quantities involved in the calculation of the current that will produce a given temperature-rise in a buried cable is as follows :—

$$H = t_1/(S + G) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$H$, the quantity of heat developed per unit length of the conductor (or conductors), is given by the equation

$$H = I^2nR(1 + at_1) \quad . \quad . \quad . \quad . \quad (2)$$

or

$$I_t = \sqrt{\left[\frac{t}{nR(1 + at)(G + S)}\right]} \quad . \quad . \quad (3)$$

where $I_t$ = current in amperes in each conductor to produce a temperature-rise of $t$ degrees C.

$a$ = temperature coefficient of the conductor, equals 0·0040 at 15° C.

$t$ = temperature-rise in degrees C. above 15·6° C.

For other symbols see List of Symbols (page 521).

*Resistance of conductor.*—In the calculation of the following current-loading tables for the specified cable sizes the values of $R$ have in all cases been derived from B.S.S. No. 7—1922, Table 2, Col. 6, by multiplication of the values there given, which are the standard resistances in ohms per 1 000 yards at 15·6° C., by the factor $10{\cdot}94 \times 10^{-6}$. The values so obtained are ohms per cm at 15·6° C.

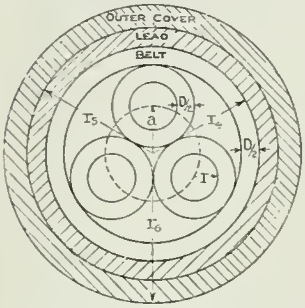


Fig. 1.—Cross-section of three-core cable, centre point not earthed.

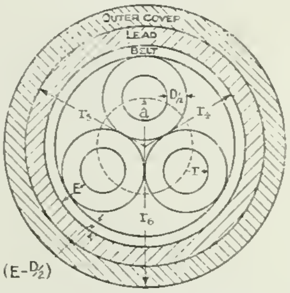


Fig. 2.—Cross-section of three-core cable, centre point earthed.

The maximum temperature-rise for armoured cables laid direct in the ground being taken as 50 degrees C. with a ground temperature of 15° C. the temperature of the conductor is limited to 65° C. as a maximum, and the resistance per cm length under these conditions is obtained by multiplying the standard resistance $R$ by

$$(1 + 0{\cdot}0040 \times 49{\cdot}4)$$ *

The first term of the formula for $I_t$ when $t$ = 50 degrees C. is therefore

$$\frac{1}{\sqrt{[R(1 + 0{\cdot}0040 \times 49{\cdot}4)]}} = \frac{0{\cdot}9129}{\sqrt{R}} \quad . \quad . \quad (4)$$

For cables in air and drawn into ducts the temperature-rise allowed is 35 deg. C., with an air temperature of 15° C., the maximum permissible temperature therefore being 50° C.

*Evaluation of G and depth of laying.*—The term $G$, on the Kennelly assumption, is defined by the following equation :—

$$G = \frac{g}{2\pi} \log_e \frac{2L}{r_6} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The depth $L$ was taken as 18 in. or 45·7 cm for cables for pressures from 660 up to and including 2 200 volts, and as 3 ft. or 91·4 cm for cables for pressures above 2 200 up to and including 11 000 volts.

The tables have been prepared for four values of thermal resistivity of the soil, viz. 340, 180, 120 and 90. It was found, however, that the best correspondence between theoretical calculations and experimental results was obtained if $g$ were taken as having only two-thirds of the value obtained by direct experimental determination. The four values of the thermal resistance $G$, corresponding to the four values of the resistivity $g$ mentioned above, are then given by the formulæ in Table 1.

Table 1.

*Thermal Resistance (G) of the Soil per cm Length of Cable, between the Outer Covering of the Cable and the Surface of the Ground.*

| Limits of Working Pressure of Cable | Thermal Resistance of Soil | |
|---|---|---|
| | $g = 340$ | $g = 180$ |
| From 660 up to and including 2 200 volts | $36{\cdot}1 \log_e \frac{91{\cdot}4}{r_6}$ | $19{\cdot}1 \log_e \frac{91{\cdot}4}{r_6}$ |
| Above 2 200 up to and including 11 000 volts | $36{\cdot}1 \log_e \frac{182{\cdot}8}{r_6}$ | $19{\cdot}1 \log_e \frac{182{\cdot}8}{r_6}$ |
| | $g = 120$ | $g = 90$ |
| From 660 up to and including 2 200 volts | $12{\cdot}7 \log_e \frac{91{\cdot}4}{r_6}$ | $9{\cdot}55 \log_e \frac{91{\cdot}4}{r_6}$ |
| Above 2 200 up to and including 11 000 volts | $12{\cdot}7 \log_e \frac{182{\cdot}8}{r_6}$ | $9{\cdot}55 \log_e \frac{182{\cdot}8}{r_6}$ |

As an example of the effect of depth of laying on the current rating, the two values of $G$ for thermal resistivity 120 may be considered. Assuming $r_6$ as 2 cm for the lower pressure cables, i.e. for

$L$ = 1 ft. 6 in., $G = 48{\cdot}5$;

for the higher-pressure cables, i.e. for

$L$ = 3 ft. 0 in., $G = 57{\cdot}3$.

Thus, if the depth be doubled the term $G$ is increased by about 18 per cent.

To obtain an indication of the effect of depth on the current-carrying capacity it may be assumed that $S$ will be a quantity of approximately the same order as $G$. The current will then be inversely proportional to the square root of the sum of these two quantities, whence it follows that the effect in this particular instance of doubling the depth at which the cable is laid will be to diminish the current-carrying capacity by some 4 or 5 per cent. This is, of course, on the assumption that the moisture content throughout the soil is the same and that the soil is thermally homogeneous.

---

* The values for the standard resistance $R$ given in B.S.S. No. 7—1922, are at 15·6° C. A temperature-rise of 50 degrees C. above 15° C. therefore corresponds to 49·4 degrees C. above 15·6° C.

*Dimensions of conductors.*—The overall diameters of the conductors for the sizes of cable dealt with in the current-loading tables are given in Table 2.

In the case of stranded conductors, the overall diameter of the conductor was derived from B.S.S. No. 7—1922, Table 2, Col. 3, and was taken as being equal to the sum of the diameters of the maximum number of component wires lying on any diameter of the strand.

*Thermal resistance of cable.*—The thermal resistance $S$ may be conveniently regarded in the case of an armoured cable as made up of two portions $S_1$ and $S_2$ such that $S_1 + S_2 = S$, and where :—

$S_1 =$ thermal resistance between the conductor (or conductors) and the sheath ;

$S_2 =$ thermal resistance between the sheath and the outer surface of the cable (protective covering).

The derivation of $S_1$ from the thermal constants assumed and the dimensions given in Table 2 above and in B.S.S. No. 7—1922, is as follows :—

$S_1 =$ resistance between conductor(s) and sheath

(*a*) Single-core cables :

$$S_1 = \frac{K}{2\pi} \log_e \left(\frac{r_4}{r_1}\right) = \frac{K}{2\pi} \log_e \left[\frac{r_1 + D}{r_1}\right] \quad . \quad (6)$$

(*b*) Concentric cables :

$$S_1 = \frac{K}{2\pi}\left[\tfrac{1}{2} \log_e \left(\frac{r_2}{r_1}\right) + \log_e \left(\frac{r_2}{r_3}\right)\right] \quad . \quad . \quad (7)$$

The value of $r_1$ is obtained from Table 2 which gives the diameter of the completed strand—

$$r_2 = r_1 + D \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where $D$ is the thickness of dielectric as specified in B.S.S. No. 7—1922.

To obtain $r_3$, the thickness $U$ of the outer conductor is added to $r_2$.

In order to obtain a simple expression for $U$ it was taken that, to a first approximation—

$$U = s/2\pi(r_1 + D) \quad . \quad . \quad . \quad . \quad (9)$$

where $s$ is the nominal area of conductor cross-section.

Therefore $r_3 = r_1 + D + s/[2\pi(r_1 + D)] \quad . \quad . \quad (10)$

and $r_4 = r_1 + 2D + s/[2\pi(r_1 + D)] \quad . \quad . \quad (11)$

so that

$$S_1 = \frac{K}{2\pi}\left\{\tfrac{1}{2} \log_e\left(\frac{r_2}{r_1}\right) + \log_e\left[\frac{r_1 + 2D + s/2(r_1 + D)}{r_1 + D + s/2(r_1 + D)}\right]\right\} \quad . \quad (12)$$

(*c*) Three-core cables (circular conductors ; centre point not earthed) :

TABLE 2.

*Sizes of Conductors dealt with in the Current-loading Tables.*

| Sectional Area of Conductor | | Number and Diameter (in.) of Wires comprising Conductor | Maximum Number of Component Wires on a Diameter | Overall Diameter of Complete Strand | |
|---|---|---|---|---|---|
| Nominal sq. in. | Calculated sq. in. | | | in. | cm |
| 0·007 | 0·007005 | 7/·036 | 3 | 0·108 | 0·274 |
| 0·01 | 0·01046 | 7/·044 | 3 | 0·132 | 0·335 |
| 0·0145 | 0·01462 | 7/·052 | 3 | 0·156 | 0·396 |
| 0·0225 | 0·02214 | 7/·064 | 3 | 0·192 | 0·487 |
| 0·03 | 0·02840 | 19/·044 | 5 | 0·220 | 0·558 |
| 0·04 | 0·03960 | 19/·052 | 5 | 0·260 | 0·660 |
| 0·06 | 0·05999 | 19/·064 | 5 | 0·320 | 0·812 |
| 0·075 | 0·07592 | 19/·072 | 5 | 0·360 | 0·914 |
| 0·1 | 0·1009 | 19/·083 | 5 | 0·415 | 1·05 |
| 0·12 | 0·1168 | 37/·064 | 7 | 0·448 | 1·14 |
| 0·15 | 0·1478 | 37/·072 | 7 | 0·504 | 1·28 |
| 0·2 | 0·1964 | 37/·083 | 7 | 0·581 | 1·47 |
| 0·25 | 0·2465 | 37/·093 | 7 | 0·651 | 1·65 |
| 0·3 | 0·3024 | 37/·103 | 7 | 0·721 | 1·83 |
| 0·4 | 0·4064 | 61/·093 | 9 | 0·837 | 2·12 |
| 0·5 | 0·4985 | 61/·103 | 9 | 0·927 | 2·35 |
| 0·6 | 0·6062 | 91/·093 | 11 | 1·028 | 2·60 |
| 0·75 | 0·7435 | 91/·103 | 11 | 1·133 | 2·87 |
| 1·0 | 1·0376 | 127/·103 | 13 | 1·339 | 3·38 |

In order to derive the dimensions needed for the calculation of the thermal resistance of a three-core cable from the thickness of the dielectric and the diameter of the conductor the following geometrical relations are required (see Fig. 1).

$$a = 1\cdot154(r + \tfrac{1}{2}D) \quad . \quad . \quad . \quad . \quad (13)$$

$$r_4 = a + r + D = 1\cdot58D + 2\cdot15r \quad . \quad (14)$$

By Equation (33) (Russell's formula for three-core cables)

$$S_1 = \frac{K}{6\pi}\log_e\left[(r_4^6 - a^6)/3r_4^3a^2r\right] \quad . \quad . \quad (15)$$

or substituting for $a$ and $r_4$ and neglecting $a^6$ in comparison with $r_4^6$

$$S_1 = K \times 0\cdot053\log_e\left[\frac{3\cdot93(D + 1\cdot37r)^3}{(D + 2r)^2r}\right] \quad (16)$$

(*d*) Three-core cables (circular conductors; centre point earthed):

Here the thickness of the belt insulation $E$ is reduced (see Fig. 2) and the formulæ are modified as follows:—

$$r_4 = a + r + E = 0\cdot58D + 2\cdot15r + E \quad . \quad (17)$$

and from Russell's formula, Equation (33) neglecting $a^6$ in comparison with $r_4^6$

$$S_1 = \frac{K}{6\pi}\log_e\left[\frac{0\cdot58D + 2\cdot15r + E}{r(2r + D)^2}\right] \quad . \quad (18)$$

In calculating $S_1$, the thermal resistivity of the dielectric was taken in general as 750 for cables for pressures up to 2 200 volts, and as 550 for cables for pressures above 2 200 volts up to and including 11 000 volts.

Higher values were taken for cables with conductors having sectional areas less than 0·06 sq. in., to allow for the difficulty in manufacturing small cables.

The value of $S_2$ the thermal resistance of the protective coverings was determined as follows:—

The outer radius of the lead sheath $r_5$ was found by adding the thickness of the lead as specified in Tables 5 to 10 of B.S.S. No. 7—1922, to the internal diameter of the lead sheath.

For single-core cables

$$r_5 = l + D + r_1 \quad . \quad . \quad . \quad . \quad (19)$$

For concentric cables

$$r_5 = l + r_4 = l + r_1 + 2D + s/2\pi(r_1 + D) \quad . \quad (20)$$

For three-core cables

$$r_5 = l + r_4 = l + 1\cdot58D + 2\cdot15r \quad . \quad . \quad (21)$$

The thickness of the armouring and protective coverings and $r_6$ the radius of the completed cable have been derived from the dimensions specified in Tables 18 and 21 of B.S.S. No 7—1922, for various sizes of cable. In order to obtain a mean value of cable covering, it has been assumed that the armouring consists of a single layer of galvanized wire. The value of the thermal resistivity determined for the protective covering, taken as a whole, i.e. wire armouring, bedding, braiding and serving, was $K_1 = 300$. This value refers to new cables only. The effect of the protective covering is small, and for the purpose of the calculations it was convenient and sufficiently accurate to regard it as being thermally homogeneous, with a mean value of thermal resistivity, $K_1 = 300$.

For $S_2$, the thermal resistance of the covering, we have

$$S_2 = \frac{K_1}{2\pi}\log_e\left(\frac{r_6}{r_5}\right) \quad . \quad . \quad . \quad . \quad (22)$$

*Three-core cables with segmental conductors.*—The increased current-ratings for three-core cables with segmental conductors are suggested tentatively, as they are based almost entirely on theoretical considerations with the adoption of certain assumptions for dimensions and shapes. Standard dimensions are required before more definite values can be given for this type of cable.

*"Skin effect" in large cables.*—The current-loading tables make no allowance for the additional heating due to "skin effect" when cables having conductors larger than 0·25 sq. in. are carrying alternating current at a frequency of 50 cycles per second or higher. Such cables are usually constructed with an inner hemp core, and are designed so as to minimize "skin effect."

*Earthed system.*—In accordance with Clause 35 of B.S.S. No. 7—1922 an earthed system is one which is permanently connected to earth in such a manner that the total earth resistance does not exceed 2 ohms, or one in which a device is installed that automatically and instantly cuts out any part of the system that becomes accidentally earthed.

TABLE 3.

660-*volt, Armoured, Single-core Cable, laid Direct in the Ground* (Table 5, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | |
|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | |
| Nominal | Calculated | $g = 340$ | $g = 180$ | $g = 120$ | $g = 90$ |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. |
| 0·007 | 0·007005 | 54 | 60 | 63 | 65 |
| 0·01 | 0·01046 | 70 | 79 | 83 | 86 |
| 0·0145 | 0·01462 | 86 | 100 | 106 | 110 |
| 0·0225 | 0·02214 | 112 | 131 | 141 | 147 |
| 0·03 | 0·02840 | 131 | 155 | 167 | 175 |
| 0·04 | 0·03960 | 160 | 190 | 207 | 218 |
| 0·06 | 0·05999 | 205 | 248 | 273 | 287 |
| 0·075 | 0·07592 | 234 | 285 | 314 | 332 |
| 0·1 | 0·1009 | 275 | 337 | 373 | 395 |
| 0·12 | 0·1168 | 299 | 367 | 407 | 435 |
| 0·15 | 0·1478 | 341 | 415 | 459 | 486 |
| 0·2 | 0·1964 | 401 | 492 | 547 | 580 |
| 0·25 | 0·2465 | 455 | 558 | 621 | 661 |
| 0·3 | 0·3024 | 510 | 627 | 699 | 743 |
| 0·4 | 0·4064 | 602 | 745 | 831 | 886 |
| 0·5 | 0·4985 | 677 | 835 | 935 | 998 |
| 0·6 | 0·6062 | 757 | 942 | 1 056 | 1 131 |
| 0·75 | 0·7435 | 848 | 1 055 | 1 186 | 1 269 |
| 1·0 | 1·0376 | 1 027 | 1 282 | 1 448 | 1 556 |

### TABLE 4.

660-*volt, Armoured, Concentric Cable, laid Direct in the Ground; Earthed or Not Earthed* (Table 5, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | |
|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | |
| Nominal | Calculated | $g = 340$ | $g = 180$ | $g = 120$ | $g = 90$ |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. |
| 0·007 | 0·007005 | 39 | 44 | 46 | 47 |
| 0·01 | 0·01046 | 50 | 57 | 60 | 62 |
| 0·0145 | 0·01462 | 62 | 72 | 76 | 79 |
| 0·0225 | 0·02214 | 81 | 94 | 101 | 105 |
| 0·03 | 0·02840 | 95 | 111 | 120 | 126 |
| 0·04 | 0·03960 | 115 | 136 | 148 | 155 |
| 0·06 | 0·05999 | 147 | 176 | 191 | 201 |
| 0·075 | 0·07592 | 168 | 202 | 221 | 233 |
| 0·1 | 0·1009 | 198 | 239 | 262 | 277 |
| 0·12 | 0·1168 | 215 | 260 | 286 | 302 |
| 0·15 | 0·1478 | 246 | 299 | 329 | 346 |
| 0·2 | 0·1964 | 289 | 353 | 391 | 413 |
| 0·25 | 0·2465 | 329 | 400 | 443 | 470 |
| 0·3 | 0·3024 | 369 | 453 | 503 | 535 |
| 0·4 | 0·4064 | 435 | 534 | 592 | 630 |
| 0·5 | 0·4985 | 486 | 605 | 675 | 718 |
| 0·6 | 0·6062 | 551 | 687 | 762 | 813 |
| 0·75 | 0·7435 | 616 | 765 | 855 | 910 |
| 1·0 | 1·0376 | 747 | 936 | 1 050 | 1 126 |

### TABLE 5.

660-*volt, Armoured, Three-core* Cable, laid Direct in the Ground; Centre Point Earthed or Not Earthed* (Table 5, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | |
|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | |
| Nominal | Calculated | $g = 340$ | $g = 180$ | $g = 120$ | $g = 90$ |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. |
| 0·007 | 0·007005 | 35 | 40 | 43 | 44 |
| 0·01 | 0·01046 | 45 | 52 | 56 | 58 |
| 0·0145 | 0·01462 | 55 | 66 | 70 | 73 |
| 0·0225 | 0·02214 | 71 | 84 | 91 | 95 |
| 0·03 | 0·02840 | 82 | 98 | 106 | 111 |
| 0·04 | 0·03960 | 100 | 120 | 131 | 138 |
| 0·06 | 0·05999 | 127 | 154 | 169 | 179 |
| 0·075 | 0·07592 | 145 | 176 | 194 | 205 |
| 0·1 | 0·1009 | 170 | 208 | 229 | 244 |
| 0·12 | 0·1168 | 185 | 226 | 251 | 267 |
| 0·15 | 0·1478 | 211 | 260 | 288 | 306 |
| 0·2 | 0·1964 | 248 | 305 | 339 | 361 |
| 0·25 | 0·2465 | 283 | 349 | 389 | 413 |
| 0·3 | 0·3024 | 318 | 391 | 436 | 465 |
| 0·4 | 0·4064 | 373 | 460 | 512 | 547 |
| 0·5 | 0·4985 | 420 | 520 | 582 | 621 |

* The current values given in this table refer to cables with circular conductors; the rating may be increased by 4 per cent for cables with segmental conductors. When two conductors only are carrying current (three-wire system, balanced load), the current values given in this table may be increased by 15 per cent.

### TABLE 6.

2 200-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 6, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| Nominal | Calculated | Outer Conductor | | Outer Conductor | | Outer Conductor | | Outer Conductor | |
| | | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 79 | 81 | 90 | 93 | 95 | 99 | 98 | 102 |
| 0·03 | 0·02840 | 92 | 94 | 106 | 109 | 113 | 117 | 117 | 121 |
| 0·04 | 0·03960 | 112 | 114 | 130 | 134 | 139 | 145 | 145 | 150 |
| 0·06 | 0·05999 | 144 | 146 | 169 | 174 | 182 | 190 | 190 | 198 |
| 0·075 | 0·07592 | 165 | 167 | 194 | 200 | 210 | 218 | 219 | 229 |
| 0·1 | 0·1009 | 194 | 196 | 230 | 236 | 249 | 258 | 260 | 272 |
| 0·15 | 0·1478 | 242 | 245 | 287 | 294 | 313 | 324 | 328 | 342 |
| 0·2 | 0·1964 | 284 | 288 | 340 | 349 | 373 | 385 | 391 | 406 |
| 0·25 | 0·2465 | 324 | 328 | 391 | 399 | 430 | 442 | 454 | 468 |

### TABLE 7.

2 200-*volt, Armoured, Three-core * Cable, laid Direct in the Ground* (Table 6, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| Nominal | Calculated | Centre Point | | Centre Point | | Centre Point | | Centre Point | |
| | | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 70 | 71 | 81 | 83 | 88 | 90 | 91 | 93 |
| 0·03 | 0·02840 | 81 | 82 | 95 | 97 | 103 | 105 | 107 | 110 |
| 0·04 | 0·03960 | 98 | 99 | 116 | 118 | 127 | 129 | 132 | 135 |
| 0·06 | 0·05999 | 125 | 126 | 150 | 152 | 163 | 165 | 170 | 174 |
| 0·075 | 0·07592 | 143 | 144 | 172 | 174 | 188 | 191 | 198 | 202 |
| 0·1 | 0·1009 | 168 | 169 | 203 | 205 | 222 | 226 | 235 | 239 |
| 0·15 | 0·1478 | 209 | 210 | 251 | 254 | 279 | 283 | 293 | 299 |
| 0·2 | 0·1964 | 245 | 247 | 297 | 301 | 329 | 335 | 348 | 355 |
| 0·25 | 0·2465 | 279 | 281 | 340 | 345 | 376 | 384 | 399 | 408 |

* The current values given in this table refer to cables with circular conductors; the rating may be increased by 3 per cent for cables with segmental conductors.

### TABLE 8.

3 300-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 7, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| Nominal | Calculated | Outer Conductor | | Outer Conductor | | Outer Conductor | | Outer Conductor | |
| | | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 79 | 80 | 92 | 95 | 100 | 103 | 104 | 108 |
| 0·03 | 0·02840 | 92 | 93 | 108 | 111 | 117 | 121 | 123 | 127 |
| 0·04 | 0·03960 | 111 | 113 | 132 | 135 | 143 | 148 | 150 | 156 |
| 0·06 | 0·05999 | 141 | 143 | 170 | 174 | 187 | 192 | 196 | 204 |
| 0·075 | 0·07592 | 161 | 163 | 194 | 199 | 214 | 220 | 226 | 234 |
| 0·1 | 0·1009 | 189 | 191 | 229 | 234 | 253 | 260 | 268 | 276 |
| 0·15 | 0·1478 | 233 | 236 | 285 | 291 | 316 | 325 | 335 | 345 |
| 0·2 | 0·1964 | 273 | 276 | 336 | 342 | 374 | 383 | 398 | 409 |
| 0·25 | 0·2465 | 312 | 314 | 385 | 391 | 430 | 437 | 458 | 469 |

### Table 9.

3 300-*volt, Armoured, Three-core* * *Cable, laid Direct in the Ground* (Table 7, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Currents (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| | | Centre Point | | Centre Point | | Centre Point | | Centre Point | |
| Nominal | Calculated | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 69 | 70 | 82 | 83 | 90 | 92 | 95 | 97 |
| 0·03 | 0·02840 | 80 | 81 | 96 | 97 | 106 | 108 | 111 | 113 |
| 0·04 | 0·03960 | 96 | 97 | 117 | 118 | 129 | 131 | 137 | 139 |
| 0·06 | 0·05999 | 121 | 122 | 149 | 150 | 165 | 167 | 176 | 178 |
| 0·075 | 0·07592 | 138 | 139 | 170 | 171 | 189 | 191 | 210 | 204 |
| 0·1 | 0·1009 | 162 | 163 | 200 | 201 | 223 | 225 | 238 | 241 |
| 0·15 | 0·1478 | 200 | 201 | 249 | 250 | 277 | 279 | 297 | 300 |
| 0·2 | 0·1964 | 235 | 236 | 293 | 294 | 329 | 331 | 352 | 355 |
| 0·25 | 0·2465 | 266 | 267 | 333 | 334 | 374 | 376 | 402 | 405 |

* The current values given in this table refer to cables with circular conductors; the rating may be increased by 2 per cent for cables with segmental conductors.

### Table 10.

5 500-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 8, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| | | Outer Conductor | | Outer Conductor | | Outer Conductor | | Outer Conductor | |
| Nominal | Calculated | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 78 | 80 | 90 | 95 | 97 | 102 | 101 | 107 |
| 0·03 | 0·02840 | 91 | 93 | 106 | 110 | 114 | 120 | 119 | 126 |
| 0·04 | 0·03960 | 110 | 112 | 130 | 135 | 140 | 147 | 147 | 155 |
| 0·06 | 0·05999 | 140 | 143 | 167 | 173 | 182 | 190 | 191 | 201 |
| 0·075 | 0·07592 | 159 | 162 | 191 | 198 | 208 | 218 | 219 | 231 |
| 0·1 | 0·1009 | 186 | 190 | 225 | 233 | 247 | 258 | 260 | 274 |
| 0·15 | 0·1478 | 231 | 235 | 280 | 289 | 309 | 321 | 327 | 342 |
| 0·2 | 0·1964 | 271 | 276 | 330 | 341 | 364 | 380 | 385 | 402 |
| 0·25 | 0·2465 | 308 | 313 | 376 | 388 | 415 | 430 | 441 | 460 |

### TABLE 11.

5 500-*volt, Armoured, Three-core* Cable, laid Direct in the Ground* (Table 8, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| Nominal | Calculated | Centre Point | | Centre Point | | Centre Point | | Centre Point | |
| | | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 68 | 69 | 81 | 83 | 89 | 90 | 93 | 95 |
| 0·03 | 0·02840 | 79 | 80 | 95 | 97 | 103 | 105 | 109 | 111 |
| 0·04 | 0·03960 | 96 | 97 | 115 | 117 | 126 | 128 | 133 | 135 |
| 0·06 | 0·05999 | 121 | 122 | 147 | 149 | 163 | 165 | 173 | 175 |
| 0·075 | 0·07592 | 138 | 139 | 168 | 170 | 187 | 189 | 198 | 201 |
| 0·1 | 0·1009 | 161 | 162 | 198 | 200 | 220 | 223 | 234 | 237 |
| 0·15 | 0·1478 | 199 | 201 | 246 | 248 | 274 | 277 | 292 | 295 |
| 0·2 | 0·1964 | 233 | 235 | 289 | 292 | 323 | 326 | 344 | 348 |
| 0·25 | 0·2465 | 264 | 266 | 328 | 331 | 369 | 372 | 393 | 399 |

* The current values given in this table refer to cables with either circular or segmental conductors.

### TABLE 12.

6 600-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 9, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| Nominal | Calculated | Outer Conductor | | Outer Conductor | | Outer Conductor | | Outer Conductor | |
| | | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 78 | 80 | 90 | 94 | 96 | 101 | 100 | 106 |
| 0·03 | 0·02840 | 91 | 93 | 105 | 110 | 114 | 119 | 118 | 125 |
| 0·04 | 0·03960 | 109 | 112 | 129 | 134 | 139 | 145 | 145 | 153 |
| 0·06 | 0·05999 | 139 | 142 | 166 | 172 | 180 | 188 | 188 | 199 |
| 0·075 | 0·07592 | 158 | 162 | 190 | 197 | 207 | 217 | 218 | 229 |
| 0·1 | 0·1009 | 186 | 190 | 223 | 231 | 244 | 255 | 257 | 272 |
| 0·15 | 0·1478 | 230 | 235 | 276 | 286 | 304 | 318 | 321 | 338 |
| 0·2 | 0·1964 | 270 | 275 | 327 | 339 | 360 | 375 | 382 | 400 |
| 0·25 | 0·2465 | 307 | 312 | 374 | 387 | 413 | 428 | 438 | 458 |

## TABLE 13.

6 600-*volt, Armoured, Three-core Cable,* laid Direct in the Ground* (Table 9, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| | | Centre Point | | Centre Point | | Centre Point | | Centre Point | |
| Nominal | Calculated | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 68 | 68 | 81 | 82 | 88 | 89 | 92 | 94 |
| 0·03 | 0·02840 | 79 | 80 | 94 | 96 | 103 | 105 | 108 | 111 |
| 0·04 | 0·03960 | 95 | 96 | 114 | 116 | 125 | 128 | 133 | 136 |
| 0·06 | 0·05999 | 121 | 121 | 147 | 149 | 162 | 165 | 172 | 175 |
| 0·075 | 0·07592 | 137 | 138 | 168 | 169 | 185 | 188 | 196 | 200 |
| 0·1 | 0·1009 | 161 | 162 | 197 | 199 | 219 | 221 | 232 | 235 |
| 0·15 | 0·1478 | 199 | 200 | 245 | 247 | 273 | 276 | 290 | 295 |
| 0·2 | 0·1964 | 233 | 234 | 287 | 290 | 321 | 325 | 341 | 346 |
| 0·25 | 0·2465 | 265 | 265 | 328 | 330 | 366 | 371 | 391 | 397 |

* The current values given in this table refer to cables with either circular or segmental conductors.

## TABLE 14.

11 000-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 10, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| | | Outer Conductor | | Outer Conductor | | Outer Conductor | | Outer Conductor | |
| Nominal | Calculated | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 76 | 79 | 87 | 92 | 93 | 100 | 96 | 103 |
| 0·03 | 0·02840 | 88 | 92 | 102 | 108 | 108 | 117 | 112 | 122 |
| 0·04 | 0·03960 | 106 | 111 | 123 | 132 | 131 | 143 | 136 | 149 |
| 0·06 | 0·05999 | 138 | 141 | 161 | 169 | 174 | 185 | 181 | 194 |
| 0·075 | 0·07592 | 156 | 160 | 183 | 192 | 198 | 211 | 206 | 221 |
| 0·1 | 0·1009 | 183 | 188 | 217 | 228 | 235 | 250 | 245 | 265 |
| 0·15 | 0·1478 | 227 | 233 | 269 | 283 | 293 | 312 | 307 | 330 |
| 0·2 | 0·1964 | 266 | 273 | 317 | 333 | 346 | 369 | 363 | 391 |
| 0·25 | 0·2465 | 302 | 310 | 362 | 380 | 395 | 422 | 416 | 447 |

## TABLE 15.

11 000-*volt, Armoured Cable, Three-core,* laid Direct in the Ground* (Table 10, B.S.S. No. 7—1922).

| Area of Conductor | | Maximum Permissible Current (Continuous Loading) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal Resistivity of Soil ($g$) | | | | | | | |
| | | $g = 340$ | | $g = 180$ | | $g = 120$ | | $g = 90$ | |
| Nominal | Calculated | Centre Point | | Centre Point | | Centre Point | | Centre Point | |
| | | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed | Not Earthed | Earthed |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 67 | 70 | 79 | 81 | 85 | 89 | 89 | 93 |
| 0·03 | 0·02840 | 78 | 80 | 92 | 95 | 100 | 103 | 104 | 109 |
| 0·04 | 0·03960 | 95 | 96 | 112 | 116 | 122 | 127 | 128 | 134 |
| 0·06 | 0·05999 | 120 | 121 | 144 | 147 | 158 | 162 | 166 | 171 |
| 0·075 | 0·07592 | 137 | 138 | 165 | 168 | 181 | 186 | 191 | 196 |
| 0·1 | 0·1009 | 160 | 162 | 193 | 198 | 213 | 219 | 225 | 232 |
| 0·15 | 0·1478 | 197 | 199 | 240 | 245 | 265 | 271 | 279 | 287 |
| 0·2 | 0·1964 | 232 | 234 | 283 | 287 | 313 | 319 | 331 | 339 |
| 0·25 | 0·2465 | 263 | 265 | 321 | 326 | 357 | 363 | 379 | 388 |

* The current values given in this table refer to cables with either circular or segmental conductors.

## TABLE 16.

660-*volt Cables in Air* (Table 5, B.S.S. No. 7—1922).

| Area of Conductor. | | Armoured | | | Unarmoured | | |
|---|---|---|---|---|---|---|---|
| Nominal. | Calculated. | Single | Concentric | 3-Core * | Single | Concentric | 3-Core * |
| sq. in. | sq. in. | amps | amps. | amps. | amps. | amps. | amps. |
| 0·007 | 0·007005 | 46 | 35 | 31 | 39 | 31 | 28 |
| 0·01 | 0·01046 | 60 | 45 | 41 | 50 | 40 | 37 |
| 0·0145 | 0·01462 | 75 | 56 | 51 | 63 | 50 | 46 |
| 0·0225 | 0·02214 | 98 | 74 | 68 | 82 | 66 | 61 |
| 0·03 | 0·02840 | 115 | 87 | 80 | 97 | 78 | 72 |
| 0·04 | 0·03960 | 141 | 109 | 99 | 120 | 98 | 90 |
| 0·06 | 0·05999 | 185 | 144 | 129 | 161 | 129 | 119 |
| 0·075 | 0·07592 | 214 | 166 | 149 | 189 | 150 | 139 |
| 0·1 | 0·1009 | 255 | 197 | 180 | 224 | 180 | 169 |
| 0·12 | 0·1168 | 280 | 216 | 197 | 249 | 198 | 186 |
| 0·15 | 0·1478 | 332 | 251 | 228 | 290 | 231 | 218 |
| 0·2 | 0·1964 | 397 | 301 | 274 | 351 | 281 | 265 |
| 0·25 | 0·2465 | 457 | 348 | 317 | 413 | 328 | 309 |
| 0·3 | 0·3024 | 522 | 397 | 361 | 475 | 377 | 355 |
| 0·4 | 0·4064 | 628 | 478 | 435 | 583 | 461 | 433 |
| 0·5 | 0·4985 | 717 | 548 | 498 | 670 | 533 | 498 |
| 0·6 | 0·6062 | 817 | 614 | — | 772 | 612 | — |
| 0·75 | 0·7435 | 933 | 712 | — | 886 | 702 | — |
| 1·0 | 1·0376 | 1 158 | 888 | — | 1 120 | 888 | — |

* The current values given in this column refer to cables with circular conductors; the rating may be increased by 4 per cent for cables with segmental conductors. When two conductors only are carrying current (three-wire system, balanced load), the current values given in this column may be increased by 15 per cent.

### TABLE 17.

2 200-*volt Cables in Air; Earthed or not Earthed* (Table 6, B.S.S. No. 7—1922).

| Area of Conductor | | Armoured | | Unarmoured | |
|---|---|---|---|---|---|
| Nominal | Calculated | Concentric | 3-Core* | Concentric | 3-Core* |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 74 | 68 | 69 | 63 |
| 0·03 | 0·02840 | 88 | 80 | 81 | 74 |
| 0·04 | 0·03960 | 107 | 98 | 100 | 91 |
| 0·06 | 0·05999 | 142 | 128 | 132 | 121 |
| 0·075 | 0·07592 | 164 | 149 | 152 | 141 |
| 0·1 | 0·1009 | 195 | 177 | 183 | 169 |
| 0·15 | 0·1478 | 247 | 225 | 233 | 217 |
| 0·2 | 0·1964 | 294 | 270 | 281 | 264 |
| 0·25 | 0·2465 | 342 | 312 | 327 | 305 |

* The current values given in these columns refer to cables with circular conductors; the rating may be increased by 3 per cent for cables with segmental conductors.

### TABLE 18.

3 300-*volt Cables in Air; Earthed or not Earthed* (Table 7, B.S.S. No. 7—1922).

| Area of Conductor | | Armoured | | Unarmoured | |
|---|---|---|---|---|---|
| Nominal | Calculated | Concentric | 3-Core* | Concentric | 3-Core* |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 80 | 72 | 74 | 66 |
| 0·03 | 0·02840 | 94 | 84 | 87 | 78 |
| 0·04 | 0·03960 | 115 | 104 | 107 | 97 |
| 0·06 | 0·05999 | 150 | 135 | 140 | 127 |
| 0·075 | 0·07592 | 173 | 156 | 161 | 147 |
| 0·1 | 0·1009 | 205 | 185 | 193 | 177 |
| 0·15 | 0·1478 | 259 | 235 | 245 | 228 |
| 0·2 | 0·1964 | 309 | 283 | 295 | 275 |
| 0·25 | 0·2465 | 359 | 326 | 344 | 321 |

* The current values given in these columns refer to cables with circular conductors; the rating may be increased by 2 per cent for cables with segmental conductors.

### TABLE 19.

5 500-*volt Cables in Air; Earthed or not Earthed* (Table 8, B.S.S. No. 7—1922).

| Area of Conductor | | Armoured | | Unarmoured | |
|---|---|---|---|---|---|
| Nominal | Calculated | Concentric | 3-Core* | Concentric | 3-Core* |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 79 | 72 | 75 | 68 |
| 0·03 | 0·02840 | 93 | 84 | 88 | 79 |
| 0·04 | 0·03960 | 115 | 104 | 109 | 98 |
| 0·06 | 0·05999 | 149 | 135 | 141 | 129 |
| 0·075 | 0·07592 | 172 | 155 | 164 | 149 |
| 0·1 | 0·1009 | 204 | 185 | 195 | 180 |
| 0·15 | 0·1478 | 257 | 235 | 248 | 230 |
| 0·2 | 0·1964 | 307 | 280 | 297 | 276 |
| 0·25 | 0·2465 | 353 | 323 | 343 | 320 |

* The current values given in these columns refer to cables with either circular or segmental conductors.

### TABLE 20.

6 600-*volt Cables in Air; Earthed or not Earthed* (Table 9, B.S.S. No. 7—1922).

| Area of Conductor | | Armoured | | Unarmoured | |
|---|---|---|---|---|---|
| Nominal | Calculated | Concentric | 3-Core* | Concentric | 3-Core* |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 79 | 72 | 75 | 68 |
| 0·03 | 0·02840 | 93 | 84 | 89 | 80 |
| 0·04 | 0·03960 | 115 | 104 | 109 | 98 |
| 0·06 | 0·05999 | 149 | 135 | 142 | 129 |
| 0·075 | 0·07592 | 172 | 156 | 164 | 150 |
| 0·1 | 0·1009 | 203 | 185 | 195 | 179 |
| 0·15 | 0·1478 | 257 | 235 | 249 | 229 |
| 0·2 | 0·1964 | 306 | 279 | 297 | 276 |
| 0·25 | 0·2465 | 353 | 322 | 344 | 320 |

* The current values given in these columns refer to cables with either circular or segmental conductors.

### TABLE 21.

11 000-*volt Cables in Air; Earthed or not Earthed* (Table 10, B.S.S. No. 7—1922).

| Area of Conductor | | Armoured | | Unarmoured | |
|---|---|---|---|---|---|
| Nominal | Calculated | Concentric | 3-Core* | Concentric | 3-Core* |
| sq. in. | sq. in. | amps. | amps. | amps. | amps. |
| 0·0225 | 0·02214 | 78 | 72 | 77 | 70 |
| 0·03 | 0·02840 | 92 | 84 | 90 | 82 |
| 0·04 | 0·03960 | 112 | 104 | 109 | 101 |
| 0·06 | 0·05999 | 148 | 135 | 146 | 132 |
| 0·075 | 0·07592 | 169 | 155 | 166 | 153 |
| 0·1 | 0·1009 | 201 | 184 | 198 | 182 |
| 0·15 | 0·1478 | 254 | 232 | 250 | 231 |
| 0·2 | 0·1964 | 301 | 275 | 298 | 277 |
| 0·25 | 0·2465 | 346 | 319 | 344 | 320 |

* The current values given in these columns refer to cables with either circular or segmental conductors.

### TABLE 22.

660-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 5, B.S.S. No. 7—1922).

| Area of Conductor | | Single | Concentric | 3-Core* |
|---|---|---|---|---|
| Nominal | Calculated | | | |
| sq. in. | sq. in. | amps. | amps. | amps. |
| 0·007 | 0·007005 | 37 | 30 | 27 |
| 0·010 | 0·01046 | 48 | 39 | 35 |
| 0·0145 | 0·01462 | 60 | 48 | 44 |
| 0·0225 | 0·02214 | 78 | 63 | 58 |
| 0·03 | 0·02840 | 92 | 74 | 68 |
| 0·04 | 0·03960 | 114 | 93 | 86 |
| 0·06 | 0·05999 | 153 | 122 | 113 |
| 0·075 | 0·07592 | 180 | 142 | 132 |
| 0·1 | 0·1009 | 213 | 171 | 161 |
| 0·12 | 0·1168 | 237 | 188 | 177 |
| 0·15 | 0·1478 | 275 | 219 | 207 |
| 0·2 | 0·1964 | 334 | 267 | 252 |
| 0·25 | 0·2465 | 393 | 311 | 294 |
| 0·3 | 0·3024 | 451 | 358 | 337 |
| 0·4 | 0·4064 | 554 | 437 | 412 |
| 0·5 | 0·4985 | 636 | 507 | 474 |
| 0·6 | 0·6062 | 733 | 581 | — |
| 0·75 | 0·7435 | 842 | 667 | — |
| 1·0 | 1·0376 | 1 065 | 843 | — |

* The current values given in this column refer to cables with circular conductors; the rating may be increased by 4 per cent for cables with segmental conductors. When two conductors only are carrying current (three-wire system, balanced load), the current values given in this column may be increased by 15 per cent.

### TABLE 23.

2 200-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 6, B.S.S. No. 7—1922).

| Area of Conductor | | Concentric | 3-Core* |
|---|---|---|---|
| Nominal | Calculated | | |
| sq. in. | sq. in. | amps. | amps. |
| 0·0225 | 0·02214 | 65 | 60 |
| 0·03 | 0·02840 | 77 | 70 |
| 0·04 | 0·03960 | 95 | 86 |
| 0·06 | 0·05999 | 125 | 115 |
| 0·075 | 0·07592 | 144 | 134 |
| 0·1 | 0·1009 | 174 | 160 |
| 0·15 | 0·1478 | 221 | 206 |
| 0·2 | 0·1964 | 267 | 251 |
| 0·25 | 0·2465 | 311 | 290 |

* The current values given in this column refer to cables with circular conductors; the rating may be increased by 3 per cent for cables with segmental conductors.

### TABLE 24.

3 300-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 7, B.S.S. No. 7—1922).

| Area of Conductor | | Concentric | 3-Core* |
|---|---|---|---|
| Nominal | Calculated | | |
| sq. in. | sq. in. | amps. | amps. |
| 0·0225 | 0·02214 | 70 | 63 |
| 0·03 | 0·02840 | 82 | 74 |
| 0·4 | 0·03960 | 102 | 92 |
| 0·06 | 0·05999 | 133 | 121 |
| 0·075 | 0·07592 | 153 | 140 |
| 0·1 | 0·1009 | 183 | 168 |
| 0·15 | 0·1478 | 233 | 217 |
| 0·2 | 0·1964 | 280 | 261 |
| 0·25 | 0·2465 | 327 | 305 |

* The current values given in this column refer to cables with circular conductors; the rating may be increased by 2 per cent for cables with segmental conductors.

### TABLE 25.

5 500-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 8, B.S.S. No. 7—1922).

| Area of Conductor | | Concentric | 3-Core* |
|---|---|---|---|
| Nominal | Calculated | | |
| sq. in. | sq. in. | amps. | amps. |
| 0·0225 | 0·02214 | 71 | 65 |
| 0·03 | 0·02840 | 83 | 75 |
| 0·04 | 0·03960 | 104 | 93 |
| 0·06 | 0·05999 | 134 | 123 |
| 0·075 | 0·07592 | 156 | 141 |
| 0·1 | 0·1009 | 185 | 171 |
| 0·15 | 0·1478 | 236 | 219 |
| 0·2 | 0·1964 | 282 | 262 |
| 0·25 | 0·2465 | 326 | 304 |

### TABLE 26.

6 600-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 9, B.S.S. No. 7—1922).

| Area of Conductor | | Concentric | 3-Core* |
|---|---|---|---|
| Nominal | Calculated | | |
| sq. in. | sq. in. | amps. | amps. |
| 0·0225 | 0·02214 | 71 | 65 |
| 0·03 | 0·02840 | 84 | 76 |
| 0·04 | 0·03960 | 104 | 93 |
| 0·06 | 0·05999 | 135 | 123 |
| 0·075 | 0·07592 | 156 | 142 |
| 0·1 | 0·1009 | 185 | 170 |
| 0·15 | 0·1478 | 237 | 218 |
| 0·2 | 0·1964 | 282 | 262 |
| 0·25 | 0·2465 | 327 | 304 |

### TABLE 27.

11 000-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 10, B.S.S. No. 7—1922).

| Area of Conductor | | Concentric | 3-Core* |
|---|---|---|---|
| Nominal | Calculated | | |
| sq. in. | sq. in. | amps. | amps. |
| 0·0225 | 0·02214 | 73 | 66 |
| 0·03 | 0·02840 | 85 | 78 |
| 0·04 | 0·03960 | 104 | 96 |
| 0·06 | 0·05999 | 139 | 125 |
| 0·075 | 0·07592 | 158 | 145 |
| 0·1 | 0·1009 | 188 | 173 |
| 0·15 | 0·1478 | 238 | 220 |
| 0·2 | 0·1964 | 283 | 263 |
| 0·25 | 0·2465 | 327 | 304 |

## THEORETICAL AND EXPERIMENTAL WORK.

Since the issue of the Preliminary Report, the investigation has been directed to obtaining the information necessary to enable final current-loading tables for cables to be drawn up. The factors regarding which further information was required, and also points which were raised in the discussion that took place on the Preliminary Report, may be included in a brief restatement of the problem.

Apart from the dielectric losses, which are negligible for the cables dealt with in this report, the maximum permissible current-loading of cables depends on the following factors:—

(*a*) The power losses in the cable.
(*b*) The thermal constants of the dielectric and protective coverings.
(*c*) The thermal constants of the surrounding soil, which depend on such factors as the moisture content and the depth of laying.
(*d*) The temperature of the ground.
(*e*) The expansion of cables.
(*f*) The maximum temperature to which it is permissible to expose the dielectric and conductor.
(*g*) The mutual influence of neighbouring cables when two or more are laid together in the same trench.
(*h*) The effect on the current-rating when cables are drawn into ducts or laid " on the solid system."
(*j*) Any modification of the rating permissible when a cable is not loaded continuously at its maximum current (this is the more usual case in practice).

The factors given above are here considered in detail, and various other points relevant to the heating of buried cables are dealt with.

### (1) POWER LOSSES IN THE CABLE.

Apart from losses occurring in the dielectric, which are negligible for the cables dealt with in this report, the power losses will depend on the current and the resistance of the conductor. Small variations may, and will be, found in individual lengths of cable, but the permissible limits of variation of conductor resistances are specified in B.S.S. No. 7—1922. As many as 29 cables were tested, details of which are given in Appendix I; and actual measurements showed that while several of the conductors were not very close to the specified dimensions, the resistivity of 230 samples of copper taken from the different cables varied only from 0·1513 to 0·1588 ohm per metre-gramme at 20° C., the higher value being probably the result of war-time and later difficulties with copper supplies.

The resistivity of the copper in cables supplied prior to 1914 rarely exceeded 0·153 ohm per metre-gramme, the usual value being 0·152 or even less.

The average temperature coefficient of 47 of the samples was 0·00390 at 20° C., or nearly 0·0040 at 15° C.

---

* The current values given in this column refer to cables with either circular or segmental conductors.

### (2) Thermal Constants of Impregnated Paper Dielectric.

The results obtained with the cables first laid suggested that the thermal resistivity of the dielectric might vary with different cables to a larger extent than had hitherto been supposed. Determinations were therefore made with all cables then available, which included a length of six-core cable for split-conductor working (each conductor circular), and one of three-core concentric split-conductor cable, provided by the Glasgow Corporation. These were supplemented later by six lengths of three-core cable from different makers, with dielectric as frequently used for 20 000-volt working, supplied through the Cable Makers' Association.

The thermal resistivity of the cables was determined by measuring the temperature of the conductor and the lead sheath by change of resistance, the dimensions of the cable being known. It was assumed that the heat distribution throughout the conductor was uniform, and also that there was no appreciable temperature gradient in the lead. All the American and German authorities have neglected any gradient in the lead sheath, and this is justified by consideration of the thermal resistivity of the lead as compared with that of a paper and oil dielectric.

The thermal resistivity of lead is 2·9, as compared with (say) 500 for the dielectric; thus, with a temperature gradient of 20 degrees C. between the conductor and the outside of the lead sheath, the gradient in the sheath would be of the order of only 0·1 degree C.

The thermal resistivity was calculated by means of the following formulæ adapted from those given by Dr. A. Russell.*

For single-core cables the thermal resistivity

$$K = \frac{2\pi(t_1 - t_2)}{H \log_e (r_4/r_1)} \quad . \quad . \quad . \quad . \qquad (23)$$

where $H$ = total heat in watts developed in each cm length of conductor.
$r_1$ = radius of the conductor.
$r_4$ = inner radius of the lead sheath.
$t_1 - t_2$ = temperature difference between the conductor and the lead sheath.

For a concentric cable

$$K = \frac{2\pi(t_1 - t_2)}{H[\frac{1}{2}\log_e (r_2/r_1) + \log_e (r_4/r_3)]} \quad . \quad . \qquad (24)$$

where $H$ = total heat in watts developed in each cm length of each conductor.†
$r_1$ = radius of the inner conductor.
$r_2$ = inner radius of the outer conductor.
$r_3$ = outer radius of the outer conductor.
$r_4$ = inner radius of the lead sheath.

And for multi-core cables

$$K = \frac{4\pi(t_1 - t_2)}{H\frac{2}{n}\log_e\left\{\frac{r_4^{2n} - a^{2n}}{nr_4^n \times a^{n-1} \times r}\right\}} \quad . \quad . \qquad (25)$$

where $a$ = radius of circle on which the centres of the conductors lie.
$H$ = total heat in watts developed in each cm length of each conductor.
$n$ = number of separate conductors in the cable.
$r$ = radius of each conductor.

The thermal resistivity $K$ thus obtained is expressed in terms of the difference of temperature in degrees C. required to cause the flow of one joule of heat per second between opposite faces of a cm cube. One joule of heat per second expressed in electrical measure is one watt, and equals 0·24 gramme-calorie per second.

The formula for multi-core cables is subject to considerable error except where the size of the conductors is very small as compared with the total diameter of the sheath. Alternative formulæ by Mie * were examined by Mr. S. Butterworth, of the National Physical Laboratory, whose conclusions are given in Appendix II. The examination indicates that Mie's formulæ are subject to considerable error and, moreover, values calculated by Russell's formula are very different from those obtained by Mie's formula. It was therefore considered advisable to make some experimental determinations to check the formulæ and to evaluate the amount of the correction required.

Various methods were considered and it was finally decided to construct an electrostatic model of the cable; this consisted of a large metal tube corresponding to the lead sheath of the cable, with three smaller tubes corresponding to the conductors placed inside. Various sets of inner tubes were available, corresponding to different sizes of conductors, and the apparatus permitted of the arrangement and spacing of the inner tubes being varied. They were carefully insulated from the outer tube and the apparatus then formed a condenser the capacity of which could be accurately determined by appropriate methods.

The thermal resistance can then be deduced by means of the analogy between electrostatic capacity and resistance.

Mr. D. W. Dye of the National Physical Laboratory gave valuable advice and assistance in connection with this electrostatic method.

The detailed account of this portion of the investigation is given in Appendix III.

As a result of this investigation the error curve shown in Fig. 36 was obtained for the Russell formula, which on account of its greater simplicity was preferred for general use (see Appendix IV).

Table 28 gives the values of thermal resistivity obtained for all the cables tested. In the case of the three-core cables two sets of values are given: (1) those evaluated by means of the Russell formula without correction as given in the Preliminary Report; and (2) the values corrected in accordance with the error curve.

The table includes also some values for bitumen filling and non-impregnated paper.

It will be seen from Table 28 that the higher values occur more generally with the older 660-volt cables, and the lower values with the modern cables as fre-

---

* "Theory of Electric Cables," p. 217 *et seq.*

† For this purpose the heat developed in the outer conductor is assumed to be the same as that in the inner conductor.

* *Elektrotechnische Zeitschrift*, 1905, vol. 26, p. 137.

TABLE 28.

*Thermal Resistivities of the Dielectrics of Cables.**

| Cable No. | Paper-insulated Cable | | Mean Value of Thermal Resistivity in Electrical Measure, $K$ | |
|---|---|---|---|---|
| | Sectional Area of Conductor, sq. in. | Working Pressure, volts | As determined | Values as Corrected after further Investigation |
| | | *Single Cables.* | | |
| 1 | 0·1 | 660 | 1 200 | — |
| 2 | 0·2 | 660 | 800 | — |
| | | *Concentric Cables.* | | |
| 3 | 0·1 | 660 | 620 | — |
| 4 | 0·1 | 660 | 1 060 | — |
| 5 | 0·1 | 660 | 1 160 | — |
| 6 | 0·2 | 660 | 1 060 | — |
| 7 | 0·2 | 660 | 1 000 | — |
| 8 | 0·2 | 660 | 870 (jute insulated) | — |
| 9 | 0·2 | 660 | 720 | — |
| 10 | 0·5 | 660 | 1 090 | — |
| | | *Three-core Cables.* | | |
| 11 | 0·025 | 660 | 1 050 | 1 330 |
| 12 | 0·05 | 11 000 | 730 | — |
| 13 | 0·1 | 6 600 | 720 | 775 |
| 14 | 0·1 | 660 | 670 | — |
| 15 | 0·1 | 6 600 | 420 | — |
| 16 | 0·15 | 6 600 | 500 | — |
| 17 | 0·15 | 20 000 | 460 | 505 |
| 18 | 0·15 | 20 000 | 550 | 600 |
| 19 | 0·15 | 20 000 | 470 | 527 |
| 20 | 0·15 | 20 000 | 550 | 618 |
| 21 | 0·15 | 20 000 | 460 | 515 |
| 22 | 0·15 | 20 000 | 570 | 640 |
| 23 | 0·2 | 20 000 | 600 | 648 |
| 24 | 0·2 | 20 000 | 600 | 648 |
| 25 | 0·2 | 3 300 | 650 | — |
| 26† | 0·2 | 20 000 | 710 | — |
| 27 | 0·25 | 11 000 | 580 | — |
| 28 | 0·15 | 3 300 | 630 | 720 |
| 29 | 0·15 | 11 000 | 510 | 560 |
| Bitumen filling | | | 511 | — |
| Paper (not impregnated) | | | 960 | — |
| Vulcanized bitumen | | | 486 | — |
| Vulcanized bitumen cables (value determined by Prof. Marchant) | | | 510 | — |

* The dimensions of the cables are given in Appendix I.

† The inner and outer conductor of each core were in parallel and treated as one conductor.

quently used for 20 000-volt working. Further investigation has been directed to obtaining values that could be considered representative of modern cables for lower pressures. For this purpose, cables Nos. 28 and 29 were obtained, and the thermal resistivities of these cables were found to be 720 and 560 respectively. The manufacturer of cable No. 28 stated that he had purposely made a cable having a high value, since this would, and in fact did, provide an additional and interesting check on the methods of calculation. As a further example, a length of large three-core 660-volt cable had a value of approximately 750.

Examination of the experimental values for different types of cable showed that generally the lower-pressure cables had a thermal resistivity somewhat greater than the higher-pressure cables had. In view of the cost of manufacture it was considered unreasonable to expect that the lower-pressure cables would normally have a value of thermal resistivity as low as that of the higher-pressure cables, and therefore the following figures were adopted as representing fair values for the different types of cables.*

| | |
|---|---|
| Cables for pressures up to and including 2 200 volts .. .. | $K = 750$ |
| Cables for pressures above 2 200 volts up to and including 11 000 volts .. .. .. | $K = 550$ |

The value of $K$ is obtained by means of the corrected Russell formula. If calculated by the uncorrected formula as in the Preliminary Report the values are more nearly 700 and 500 respectively.

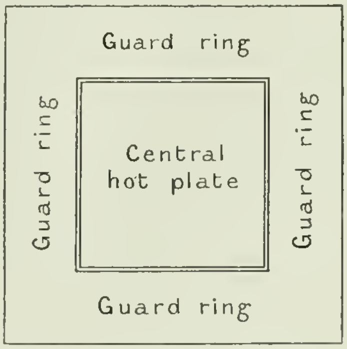


FIG. 3.—Diagram of apparatus for the determination of the thermal resistivity of soil.

### (3) THERMAL CONSTANTS OF THE SURROUNDING SOIL.

(*a*) *Thermal resistivity.*—Dr. E. Griffiths of the N.P.L. Heat Department has determined experimentally the thermal resistivity of soil with varying amounts of moisture content.

The apparatus consists of a flat central plate, electrically heated and surrounded by a guard ring (see Fig. 3). The guard ring consists of an outer plate in the form of a ring, in the same plane with the central plate but separate from it. The guard ring is maintained at the same temperature as the central part, but the electrical power supplied to the central part is measured separately from that supplied to the guard ring.

---

* Higher values have been adopted for cables with conductors having a sectional area less than 0·06 sq. in. to allow for the difficulty in manufacturing small cables.

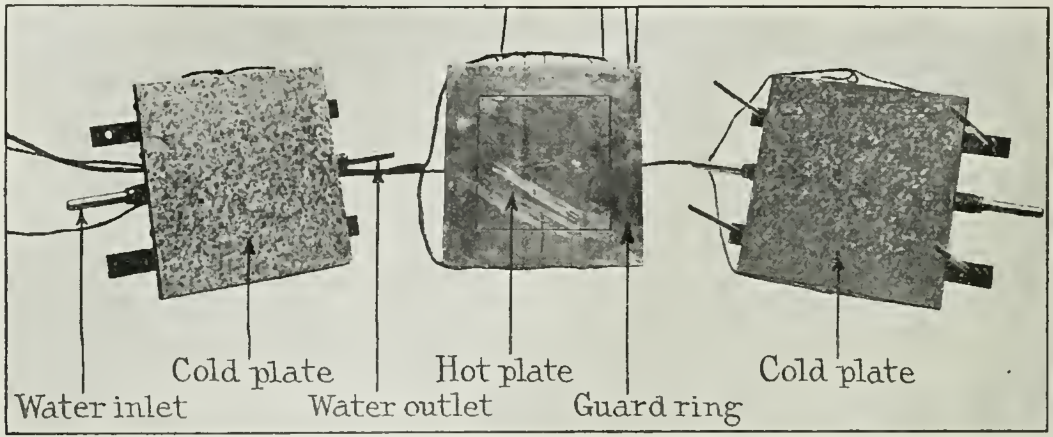


Fig. 4.—Apparatus for the determination of the thermal resistivity of soil.

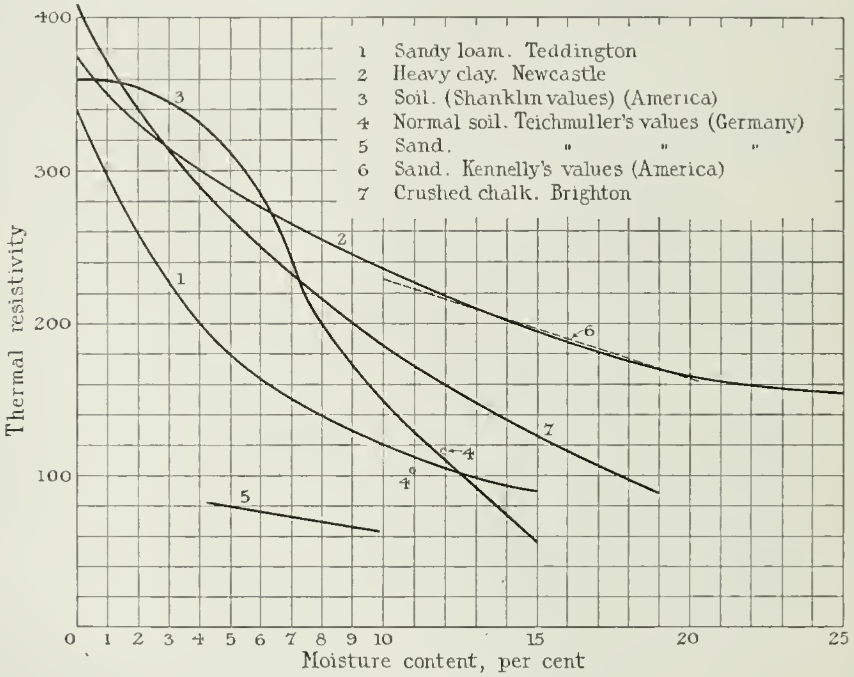


Fig. 5.—Thermal resistivity and moisture content of soil.

At a distance of 1 in. from the hot plate were two other plates cooled by water circulation and maintained at a constant temperature.

Fig. 4 shows the apparatus before assembly; the hot plate with the guard ring is in the centre and the cold plates are on either side.

The soil was packed in wooden frames with zinc faces the size of the hot plate, and these were sealed in waxed paper envelopes. Thermo-couples of copper constantan were soldered to various points on the zinc faces. The frames were sandwiched between the hot and cold plates and surrounded with granulated cork.

The heat transmitted through the specimens was determined from observations of the watts dissipated in the hot plate. Before the final observations were taken, ample time was allowed for equilibrium to be attained, and the observations extended over a period of several days.

The range of temperature over which the test was made was from 15° C. to 25° C.; the temperature interval was kept as small as practicable in order to avoid disturbing unduly the distribution of moisture.

The resultant values are given in the curve shown in Fig. 5, which includes also values deduced from

Shanklin's results,* two values from Teichmüller and a curve from Kennelly's figures.

Two series † of observations were made at the N.P.L., one on the sandy loam soil of Teddington, and the other on heavy clay soil from the Newcastle district. It will be seen from Fig. 5 that the values for the two types of soil are markedly different ; the clay is nearly the same as the sandy loam when both are dry, but it is considerably higher than the sandy loam when damp.

The N.P.L. values are quite regular, and the Shanklin curve for light soil agrees only at the extreme ends, the difference with moisture contents of from 1 per cent to 8 per cent being large. The two values of Teichmüller are near the point at which the N.P.L. and Shanklin curves cross, and are in fair agreement at this point. Kennelly's values for sand, however, agree closely with the N.P.L. curve for stiff clay.

(*b*) *Moisture content.*—The moisture content of the soil varies considerably from time to time and place to place. At Teddington in a normal year the moisture content varies from 9 per cent to 15 per cent, the latter figure being more usual during the winter. In the abnormal year of 1921 the values at 2 ft. depth taken at the N.P.L. are given in Table 29.

TABLE 29.

*Moisture Content of Soil at Teddington in* 1921 *and* 1922.

| Date | Moisture Content, per cent |
|---|---|
| 8th July, 1921 .. .. | 4·5 |
| 20th November, 1921 .. | 8·0 |
| 12th January, 1922 .. | 14·0 |
| 22nd April, 1922 .. | 12·0 |

Observations taken by Mr. M. Farrer, Engineer and Manager to the Twickenham and Teddington Electric Supply Co., showed that in the neighbourhood of Teddington the values were from 10 per cent to 14 per cent up to June 1921, but that at Claygate, a few miles away, where the soil is clay and the height above sea level much greater than at Teddington, at one place the exceptionally low values of from 1·6 per cent to 2·8 per cent were obtained in November 1921.

These low values are apparently not due to drying of the soil by the heat from the cable, since in one case in which observations were taken the moisture content immediately against the cable was 2 per cent, and at 18 in. away from it was 1·9 per cent.

In the Newcastle-upon-Tyne district the figures for the latter part of 1920 showed that the moisture content varied from 14 per cent to 38 per cent, the more general value being about 20 per cent. From April to June 1920 the values varied from 8 per cent to 39 per cent. For 1921, the values varied from 4 per cent to 28 per cent. Other towns show differences of much the same order. The late Mr. G. L. Black obtained values at Glasgow in 1920 varying from 11 per cent to 29 per cent, and the values obtained by Mr. J. Christie at Brighton in 1921 varied from 15 per cent to 21 per cent.

In Buenos Aires, during May and June 1921, Mr. J. Wilson determined the moisture content at 20 different places, and the values varied from 16 per cent to 28 per cent, the average being 21·4 per cent.

The statement given above is a short summary of the overall limits of the values observed. It will be appreciated that the moisture content will vary with different types of soil, and with climatic conditions, and that where cables are being run continuously at approximately the maximum current-loading, observations should be made of the moisture content with a view to ascertaining the minimum to be expected under full-load conditions. This is particularly necessary where cables are laid close to the surface and where the moisture content would probably be lower than at a greater depth. A large number of observations has been made, and while it is clear that it is impossible to provide data capable of general application, the series of observations taken in the Newcastle-upon-Tyne district are given in Appendix V for the purpose of showing the order of variation that might be expected both at different times of year and in various types of soil at the same time.

Engineers have from time to time drawn attention to the drying action of a heated cable, and have stated that with a continuously loaded cable the soil in the immediate vicinity becomes quite dry ; but although in the course of the investigation definite evidence on this point has been sought, it has not been obtained.

It is extremely rare for soil to have a less moisture content than 5 per cent, even when appearing to be quite dry. Moreover, practical tests have shown that the soil immediately surrounding a cable running continuously on full load for a week was distinctly wetter than that at distances of 1 and 2 ft. away horizontally, values of moisture content of 18, 16 and 14 per cent respectively being obtained. These values occurred in open country in stiff clay at several points that had not been disturbed previously for 12 years. It is common experience to find the cable trench many years after excavation acting as a drain to the surrounding country.

When cables are required to be loaded for long periods at their maximum current, attention should be paid to the condition of the soil in view of the large difference in current-carrying capacity for the extremes that may be met with.

It was decided : (1) To adopt the series of values connecting moisture content and thermal resistivity obtained at the N.P.L., and (2) to prepare four sets of tables of maximum permissible currents for armoured cables laid direct in the ground, and values for armoured and unarmoured cables in air, and for unarmoured cables drawn into ducts.

It was also decided that the current-loadings in the four sets of tables for armoured cables laid direct in the ground should correspond to the values of moisture content and thermal resistivity of the soil given in Table 30.

In the case of heavy clay soil with moisture content greater than that given above, the value of the thermal resistivity is not reduced appreciably; for instance, with a moisture content of 25 per cent the thermal resistivity is approximately 150 (see Fig. 5).

---

* *Journal of the American Institute of Electrical Engineers* 1922, vol. 41, p. 92.

† For values for chalk see Appendix VIII.

(*c*) *Depth of laying.*—The experimental work to determine the effect of the depth of laying, published in the Preliminary Report, has been compared with theoretical formulæ. In the experimental work three lengths of 0·1 sq. in. three-core 660-volt cable were laid at Newcastle-upon-Tyne at depths of 1·5, 2·5 and 4·5 ft. respectively, and the heating was determined.

The general formula shows the importance of the term $G$, the thermal resistance of the ground. The question of the depth of laying is therefore intermixed with the question of the validity of the assumption regarding the heat flow, but in order to show more clearly the comparison between experimental and calculated results, the question of the depth of laying may be considered here, comparing the values obtained with those calculated by means of the formula finally adopted.

TABLE 30.

*Values of Thermal Resistivity and Moisture Content of Soil on which the Current-loading Tables are based.*

| Thermal Resistivity of Soil, $g$ | Approximate Moisture Content of Soil | | |
|---|---|---|---|
| | Sandy Loam | Heavy Clay | Chalk |
| 340 | 0 | 1 % | 2 % |
| 180 | 5 % | 17 % | 10 % |
| 120 | 10 % | — | 16 % |
| 90 | 15 % | — | 20 % |

The heating of a buried cable is governed by the relation—

$$H = t/(G + S) \quad . \quad . \quad . \quad . \quad (26)$$

where $H$ = total heat in watts developed in each cm length of each conductor.

$t$ = temperature-rise of the conductor above the datum level.

$S$ = thermal resistance of the dielectric and the protective coverings surrounding the conductor.

$G$ = thermal resistance of the earth between the protective covering of the cable and the external isothermal.

For a cable of the type considered, $S$ is approximately 35 and the three values of

$$G = \frac{g}{2\pi} \log_e \left(\frac{2L}{r_6}\right) \quad . \quad . \quad . \quad . \quad (27)$$

corresponding to the three depths of laying specified, are as follows:—

For $L = 1{\cdot}5$ ft., $G = 54{\cdot}0$.
,, $L = 2{\cdot}5$ ft., $G = 60{\cdot}5$.
,, $L = 4{\cdot}5$ ft., $G = 68{\cdot}0$.

Comparing first the experimental results obtained, the average increase in temperature-rise in a cable laid at 2·5 ft. below the surface of the ground was 4 per cent (the mean of a series of values ranging from 0·7 to 7·4 per cent) over that of a similar cable carrying the same current and laid at 1·5 ft. below the surface.

According to the general formula, the ratio of temperature-rise in the two cases is given to a first approximation by the equation—

$$\frac{t}{t'} = \frac{S + G'}{S + G} = \frac{35 + 60{\cdot}5}{35 + 54{\cdot}0} = 1{\cdot}07 \quad . \quad (28)$$

or the temperature-rise at 2·5 ft. is 7 per cent greater than at 1·5 ft.

The average increase of temperature-rise in a cable laid at 4·5 ft. below the surface was 15·7 per cent over that of a similar cable carrying the same current laid at 1·5 ft. This was the mean of a series of results ranging from 10·8 to 18·95 per cent.

The calculated value for this case is

$$\frac{t}{t'} = \frac{35 + 68}{35 + 54} = \frac{103}{89} = 1{\cdot}16$$

In computing the current-loading tables it was decided to adopt 18 in. as the depth of laying for cables for pressures up to and including 2 200 volts, and 3 ft. for cables for pressures above 2 200 volts up to and including 11 000 volts, the dimension being in each case the distance from the surface of the ground to the axis of the cable.

### (4) TEMPERATURE OF THE GROUND.

A large amount of information has been collected on the actual temperature of the ground in different parts of the world. For Britain, full information is available in the reports of the Meteorological Office, and these are shown in Fig. 6. The values for Calcutta and various parts of Australia, which have been furnished through Mr. B. Welbourn, are shown in Figs. 7, 8, 9, 10 and 11.

It will be seen from Fig. 6 that even in the abnormal year of 1921 the maximum ground temperature at a depth of 2 ft. was only approximately 20° C. and that during the greater part of the year the value was lower than 15° C. (the Australian figures are not greatly higher than these).

It was appreciated that the highest ground temperature coincided with the period when the peak load would be in general a minimum, and it was decided to adopt a value of 15° C. as representing the average temperature on which current-loading tables should be based.

### (5) EXPANSION OF CABLES.

The extent to which the conductor and the lead sheath of a cable expand is a factor which requires consideration in connection with current-rating. The total expansion as a result of heating may be taken up in various directions, but the differential expansion between the lead and the copper gives an indication of the internal stresses to which the cable is subjected.

The expansion that would be expected can be calculated from the coefficient of expansion of the materials and from knowledge of the temperature. Taking the following coefficients:—

| | |
|---|---|
| For copper .. .. | 0·0000168 for 1 degree C. |
| For lead .. .. | 0·0000275 ,, ,, |

and taking values of temperature from actual observations in which the rise of temperature of the lead sheath is about one-half that of the conductor, the expansion per 100 yards' run after steady conditions have been reached in a cable as used for 20 000 volts is as follows :—

| | |
|---|---|
| Conductor . . | 0·6 in. for 10 degrees C. temperature-rise of conductor. |
| Lead sheath. . | 0·47 in. for 10 degrees C. temperature-rise of conductor. |

For an 11 000-volt cable :—

| | |
|---|---|
| Conductor . . | 0·6 in. for 10 degrees C. temperature-rise of conductor. |
| Lead sheath. . | 0·58 in. for 10 degrees C. temperature-rise of conductor. |

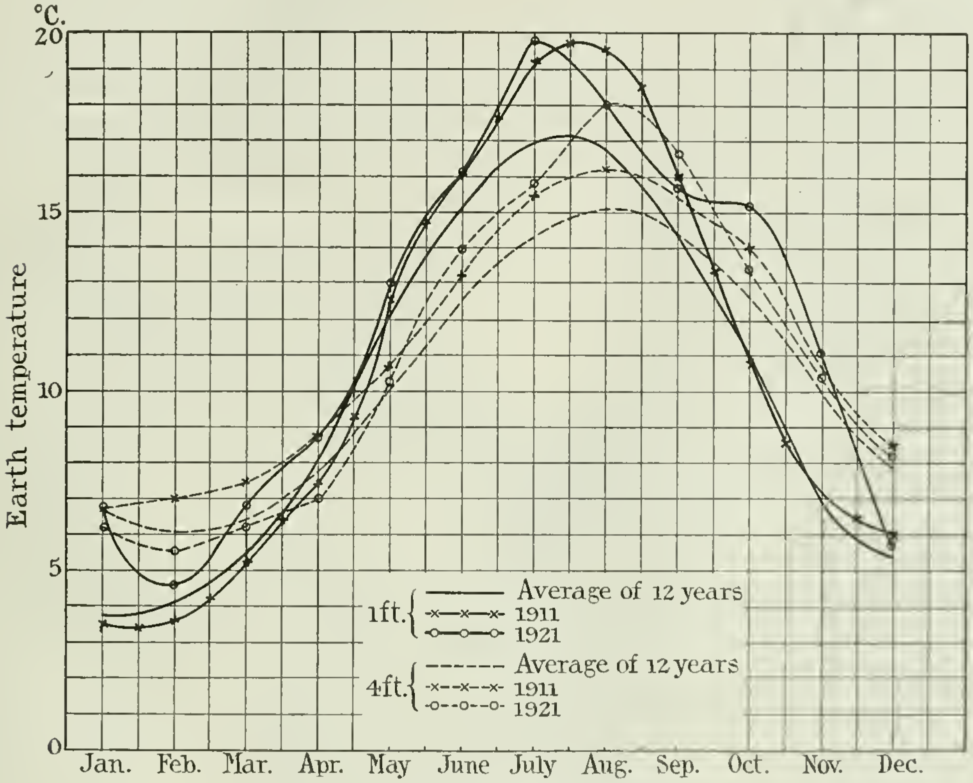


Fig. 6.—Earth temperatures at Kew.

For a 3 300-volt cable :—

| | |
|---|---|
| Conductor . . | 0·6 in. for 10 degrees C. temperature-rise of conductor. |
| Lead sheath. . | 0·56 in. for 10 degrees C. temperature-rise of conductor. |

Thus in these examples the differential expansion is small, the difference of temperature between conductor and sheath being compensated for by the difference in the coefficient of expansion.

It appeared to be possible that the conditions of continuous loading did not necessarily represent the most severe conditions, since in the early part of the heating the difference of temperature between the conductor and the sheath might be greater than when the steady condition is reached. As a further example, therefore, a 0·15 sq. in. 11 000-volt cable laid direct in the ground was tested 2 hours after the current (220 amperes) had been switched on, and the results were as follows :—

| | |
|---|---|
| Temperature-rise of lead sheath . . | 8 degrees C. |
| Temperature-rise of conductor . . | 18 degrees C. |

Under these conditions the calculated

Expansion of 100 yards of conductor would be 1·09 in.

Expansion of 100 yards of sheath would be 0·74 in.

It is apparent, however, that with an armoured three-core cable in which the cores are twisted around each other the linear expansion is considerably less than the above values would indicate. Some tests by a large firm of cable makers gave results which, when reduced to a basis comparable with the above, are as follows :—

For a 0·15 sq. in. three-core high-voltage armoured cable laid out along a floor :—

| | |
|---|---|
| Temperature-rise of conductor . . | 40 degrees C. |
| Temperature-rise of sheath . . | 20 degrees C. |
| Differential expansion between conductor and sheath . . . . | 0·024 in. |
| Differential expansion between sheath and ground . . . . | 0·9 in. |

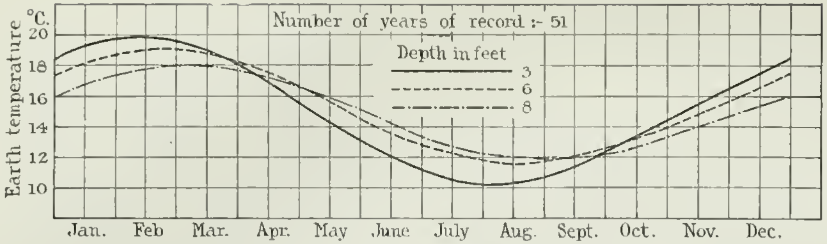


FIG. 7.—Earth temperatures at Melbourne (Australia).

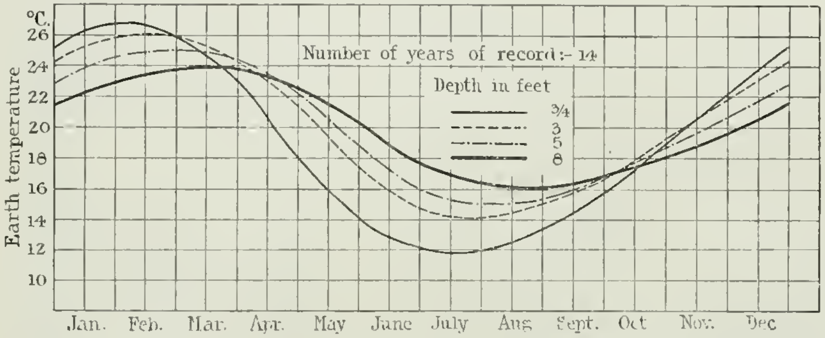


FIG. 8.—Earth temperatures at Perth (Australia).

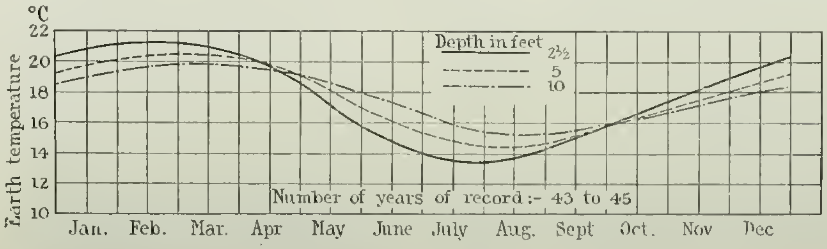


FIG. 9.—Earth temperatures at Sydney (Australia).

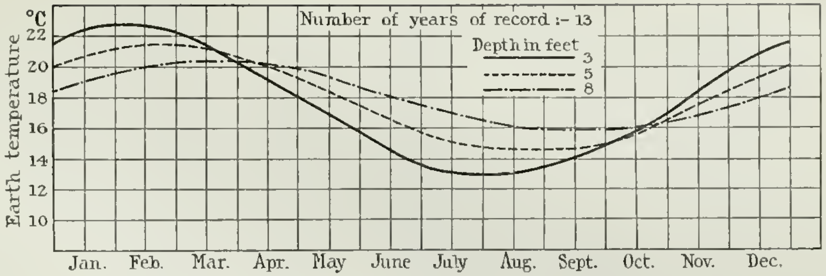


FIG. 10.—Earth temperatures at Adelaide (Australia).

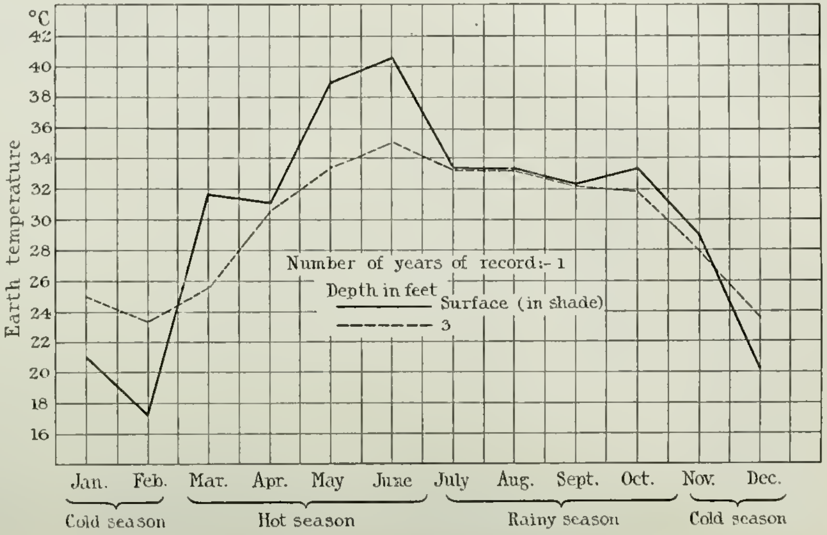


FIG. 11.—Earth temperatures at Calcutta (India).

Had the lead and copper expanded freely the expansion would have been :—

Copper = 2·35 in.
Lead = 2·0 in.
Armouring = 0·9 in.

The conclusion drawn was that the copper and lead expanded by the amount of the expansion of the armouring only, the frictional grip of the paper around the copper and that of the armouring around the lead and the paper under the lead being sufficient to prevent any further expansion.

The lead and copper therefore will be in a state of longitudinal compression and the resultant expansion may be radial.

Apart from the temporary expansion, results of actual measurements by Beaver * indicate that after a cable has been heated and cooled a permanent set is produced, the amount and direction of which varies in different parts of the cable. A result of this kind may apply only to the exact condition under which the particular tests were made and does not necessarily hold for all conditions of laying; at the same time, however, the values obtained are of great interest and significance.

### (6) MAXIMUM PERMISSIBLE TEMPERATURE FOR PAPER-INSULATED CABLES FOR PRESSURES UP TO AND INCLUDING 11 000 VOLTS.

The question as to the maximum temperature to which the impregnated paper dielectric can be exposed for long periods without fear of deterioration, either mechanical or electrical, is one on which various authorities are somewhat in conflict. The present permissible temperatures for various countries are as follows :—

(1) American (I.E.E.) .. .. 85° C., less 1 degree C. for each 1 000 volts increase.
(2) German (V.D.E.) .. .. 50° C.
(3) French (Laboratoire Central) 50° C.

In 1921 the following figures were suggested by various American investigators ** :—

(4) Del Mar † .. .. .. 85° C. to 90° C.
(5) Elden ‡ .. .. .. 85° C.
(6) Torchio § .. .. .. 105° C. to 110° C.
(7) Fisher and Atkinson ‖ .. 85° C.
(8) Roper ¶ .. .. .. 110° C.

These later values are all based on consideration of the mechanical properties of the paper only, and from this point of view alone the suggested limit of 80° C. to 85° C. is probably quite reasonable, and is confirmed by the preliminary experiments at the National Physical Laboratory published in the Preliminary Report.

In June 1922, Roper published results ¶ showing that at the normal operating temperature a large number of breakdowns occurred on cable systems, apparently due mainly to heating in the dielectric.

The German values are based on the dielectric losses, 50° C. being the point at which according to their earlier investigations these losses become appreciable. Considerable improvement has been effected in recent years in this respect and it appeared probable on the information available that from the point of view of the dielectric only a temperature of 80° C. might be adopted, especially as the dielectric losses of the cables dealt with in the current-loading tables are so small that they can be neglected.

After full consideration of all the various factors involved it was decided to adopt 65° C. (that is allowing a rise of temperature of 50 degrees C. above the value of 15° C. taken as the normal temperature of the ground) for the maximum temperature of the conductor for armoured cables up to and including 11 000 volts working pressure, laid direct in the ground. Here emphasis has been laid on the heavy cost of replacing underground mains and the long life and reliability of operation which are required for such cables. Moreover, it was appreciated that :—

(*a*) There was danger of mechanical trouble with an excessive temperature owing to the movement of the cable relative to the earth or duct.

(*b*) For the higher-pressure cables it was desirable to err on the side of safety, while for the lower-pressure cables it would not be economical to run at high temperatures, since owing to the operation of Kelvin's law the cost of the energy losses would be in excess of the saving in copper.

The actual difference in permissible current-loading between rises of 50 degrees C. and 65 degrees C., corresponding to final temperatures of 65° C. and 80° C. respectively, is approximately 12 per cent.

In view of the fact that a cable drawn into a duct is free to move lengthways along the duct and cause injury to the lead by abrasion, it was considered that the permissible temperature should be lower than that for cables laid direct in the ground. It was decided, therefore, to adopt 50° C. for the maximum temperature of the conductor for plain lead-sheathed cables drawn into ducts, this value corresponding to a temperature-rise of 35 degrees C.

### (7) SUMMARY OF PROPOSED BRITISH CONSTANTS AND THOSE ADOPTED BY OTHER COUNTRIES.

In Table 31 is given a summary of the various constants now proposed, as the result of this investigation, for the calculation of current-loading tables. The corresponding constants adopted by the French, German and Japanese authorities are given for comparison.

British : Values refer to one cable. It is recommended that where two cables are laid in the same trench and in the same horizontal plane the current should be reduced in the following ratios (see Table 37, page 549) :

Four inches between axes .. 0·76
Eight inches between axes .. 0·82
Twelve inches between axes .. 0·86

French : Values refer to one cable. It is recommended that where more than one cable is laid in the same trench the current should be reduced in the following ratios :—

---

* *Journal I.E.E.*, 1915, vol. 53, p. 57.

** See Addendum on page 561.

† *Journal of the American Institute of Electrical Engineers*, 1921, vol. 40, p. 131.

‡ *Ibid.*, 1921, vol. 40, p. 145.

§ *Ibid.*, 1921, vol. 40, p. 96.

‖ *Ibid.*, 1921, vol. 40, p. 183.

¶ *Ibid.*, 1921, vol. 40, p. 201.

| | |
|---|---|
| Two cables .. | .. 0·84 |
| Three cables .. | .. 0·76 |
| Larger number .. | .. 0·55 |

German : Values refer to two cables laid in the same trench.

(8) Representation by General Formula.

The calculation of the temperature-rise of a buried cable is based upon the relation :—

$$H = t/(S + G) \quad . \quad . \quad . \quad . \quad . \quad (29)$$

The calculation of the thermal resistance $S$ in the case of a single conductor is

$$S = \frac{K}{2\pi} \log_e \left(\frac{r_4}{r_1}\right) \quad . \quad . \quad . \quad . \quad . \quad (30)$$

Russell's formula for the thermal resistance of unit length of a multi-core cable is :—

$$S = \frac{K}{2\pi n} \log_e \frac{(r_4^{2n} - a^{2n})}{n r_4^n a^{n-1} r} \quad . \quad . \quad . \quad . \quad (33)$$

Various suppositions have been made regarding a suitable expression for $G$, the thermal resistance of the soil surrounding the cable. Kennelly * supposed that the surface of the ground above the cable might be regarded for practical purposes as a plane isothermal. On this supposition, applying the method of electrical images as in Foster and Lodge's paper (*Philosophical Magazine,* 1875) it can be shown that

$$G = \frac{g}{2\pi} \log_e \left\{\frac{2l}{2r_6} + \sqrt{\left(\frac{l^2}{r_6^2} - 1\right)}\right\} \quad . \quad . \quad (34)$$

Table 31.

*Summary of Proposed British Constants and those Adopted in the Calculation of Foreign Current-loading Tables.*

| Constants | British (now proposed) | | French | German | Japanese |
|---|---|---|---|---|---|
| | Laid Direct in the Ground | Drawn into Ducts | | | |
| Permissible temperature-rise of conductor | 50 deg. C. | 35 deg. C. | 40 deg. C. | 25 deg. C. | 85 deg. C. |
| Maximum permissible temperature | 65° C. | 50° C. | 50° C. | 50° C. | 100° C. |
| Temperature of soil .. .. | 15° C. | 15° C. | 10° C. | 25° C. | 15° C. |
| $K$ of soil .. .. .. .. | 340, 180, 120 and 90 | — | 200 | 100 | 324‡ |
| $K$ of cable .. .. .. | 550 and 750 | 550 and 750 | 230* | 500† | 636 |
| Depth of laying .. .. | 1 ft. 6 in. and 3 ft. | — | Not specified | 2 ft. 3 in. | 3 ft. |

* The very low value here is not the result of experiment, but appears to have been adopted after examination of the values given by various investigators. It would seem probable that there is an error in the French values due to a misunderstanding as to the units in which the thermal resistivity is expressed.

† This corresponds to the British value of 550.

‡ Dry sand.

The same formula applies to the external armouring when this is present, the thermal resistance being then the sum of two such terms, so that

$$S = \frac{K}{2\pi} \log_e \left(\frac{r_4}{r_1}\right) + \frac{K'}{2\pi} \log_e \frac{r_6}{r_5} \quad . \quad . \quad . \quad (31)$$

The thermal resistance of the lead sheath is regarded as negligible. In the concentric cable the thermal resistance between the conductors and the sheath, the thermal resistance of the outer conductor being neglected, is given by the formula :—

$$S = \frac{K}{2\pi}\left[\tfrac{1}{2} \log_e \left(\frac{r_2}{r_1}\right) + \log_e \left(\frac{r_4}{r_3}\right)\right] \quad . \quad . \quad (32)$$

In the case of a multi-core cable two or three different formulæ are available for the calculation of the thermal resistance from the thermal resistivity, or vice versa. These are fully dealt with in the section on page 565.

Here $l$ is very closely the depth of the cable axis below the surface of the ground, and for the purposes of this investigation $l = L$.

Usually $l^2/r_6^2$ is large compared with unity. For example, taking $l = 18$ in. and $d = 3$ in., $l^2/r_6^2 = 144$. The expression for $G$ can therefore be simplified and written in the form

$$G = \frac{g}{2\pi} \log_e \left(\frac{2L}{r_6}\right) \quad . \quad . \quad . \quad . \quad . \quad (35)$$

In this form it was used by Teichmüller and others (see "Die Erwärmung der Electrischen Leitungen," p. 53).

The basic assumption here is that the surface of the earth above the cable, because of the free dissipation of heat due to radiation and convection through the ambient air, forms an isothermal surface, and this henceforward will be referred to as the Kennelly assumption.

---

* *Electrical World,* 1893, vol. 22, p. 183.

Other and simpler assumptions have been proposed by various investigators, e.g. that due to Apt, references to which occur in other parts of this report. Apt suggested that as a first approximation the effect of the earth surrounding the cable should be considered to be equivalent to that of a cylinder of material equal in thermal resistivity to the soil and having a radius equal to the depth of the cable axis below the surface of the ground. On this assumption,

$$G = \frac{g}{2\pi} \log_e \left(\frac{L}{r_6}\right) \quad . \quad . \quad . \quad . \quad . \quad (36)$$

The heat generated, $H = nI_2R_1$ . . . . . . . (37)

where $I =$ current.

$n =$ number of conductors.

$R_1 = R(1 + 0\cdot004\,t)$, the resistance in ohms per cm of the cable at working temperature, taking the temperature coefficient of copper as 0·004.

The formula for the determination of the current to produce a given temperature-rise of the conductor $t_1$ is therefore

$$I = \frac{1}{\sqrt{[nR(1 + 0\cdot004\,t_1)]}} \sqrt{\left(\frac{t_1}{S + G}\right)} \quad . \quad (38)$$

It was considered, however, that the assumptions regarding the heat-flow through the surrounding soil were not justified, and an attempt has therefore been made to determine experimentally the actual shape of the isothermals surrounding a buried cable. Kennelly and Teichmüller assumed that the boundary of the earth and air formed an isothermal plane, but practical experience suggested this was not strictly accurate, as cases are well known of the route of a heavily loaded cable being clearly traceable by the drying of the surface of the soil immediately over it, which suggested a higher temperature of the ground surface immediately above the cable.

Previous work on buried cables had shown that many variable factors existed and that tests made on ordinary soil would probably be seriously influenced by

(*a*) Lack of homogeneity.
(*b*) Change in moisture content with position and time.
(*c*) Inconstant weather conditions.

The test to be made had therefore to be under cover—

(*a*) In homogeneous material.
(*b*) Of constant moisture content.
(*c*) In practically still air at a reasonably constant temperature.

The question of the best material to use was considered at length, and the relative advantages and disadvantages of bitumen, dry sand and other materials were reviewed, which resulted in sand being chosen, chiefly because of the elaborate precautions necessary with bitumen and allied compounds to prevent displacement of the measuring thermo-couples during shrinkage on cooling.

The test was made on as large a scale as practicable, a rectangular box, 3 ft. square and 4 ft. 6 in. high, being built strong enough to contain 2 tons of specially dried sand. For the first test, the conductor was a metal tube 0·7 in. external diameter placed vertically in the box on one centre line, 1 ft. from one boundary. This gave a ratio of 35 for the depth of laying to the radius of the cable, a very similar value to that assumed by Teichmüller.

The measurement of temperature distribution was made by means of 40 specially constructed thermo-couples standardized by the National Physical Laboratory, the hot junctions lying in a horizontal plane halfway up the box, the thermo-couple wires being stretched vertically so as not to disturb the lines of heat-flow. These thermo-couples were arranged on lines radial from the conductor and as accurately positioned as possible. The sand was then gently sifted in until the box was full, and, after settling down, the thermo-couples were checked.

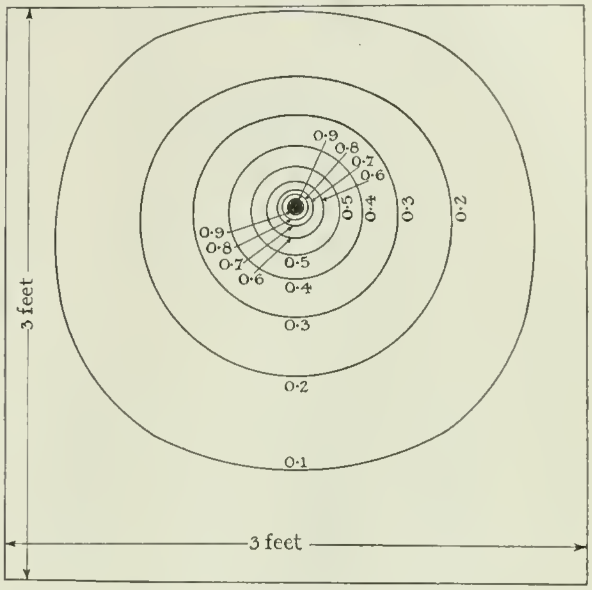


Fig. 12.—Isothermals in dry sand.

The current was set to maintain a temperature-rise of 55 degrees C. and this current corresponded to 7·7 watts per foot run. Conditions were maintained as steady as possible for one week, when readings at all the thermo-couples were taken, from which the chart shown in Fig. 12 was plotted. A further set of readings one week later were in substantial agreement.

The cylindrical surface corresponding to the relative temperature-rise (1·0) coincides with the outer surface of the cable, and the other isothermals are decimal parts of this down to 0·1. As the boundaries of the sand in this test were in no direction very much greater than the depth of laying, it was considered of interest to make a further test with those boundaries relatively much further off. This was done by sinking a new conductor 3 in. from one boundary, on the same centre line as the metal tube. The diameter of this conductor was chosen to give the same ratio (35) as before. The thermo-couples were not quite so satisfactorily placed for this test, but they could not, of course, be disturbed; their position was accurately known, and it was possible to draw a temperature distribution chart in this case also (see Fig. 13). The temperature-rise was as before, corresponding to 6·55 watts per foot run, and readings were taken after the current had been maintained for one week.

In this chart (Fig. 13) the isothermals above 0·5 are omitted for clearness, as they are evidently circles nearly concentric with the conductor, but all the isothermals for 0·15 and below cut the ground boundary.

These results indicate that the assumptions regarding the lines of heat-flow do not correspond to the observed facts, and, as will be shown later, it is necessary to modify one of the terms of the formula in order to obtain satisfactory agreement between experimental and calculated values.

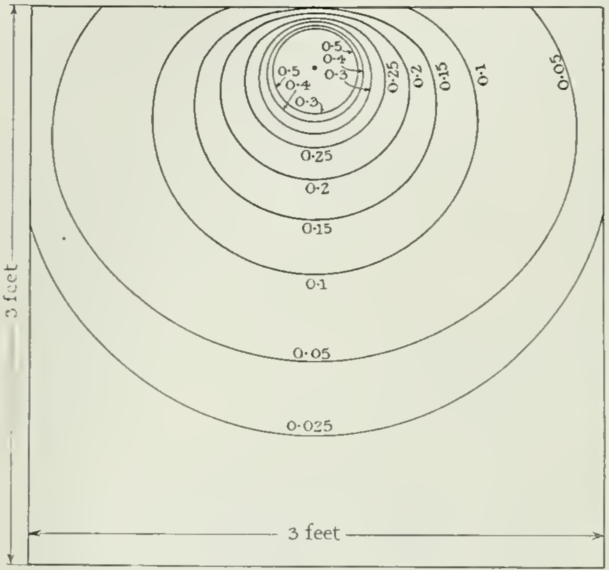


Fig. 13.—Isothermals in dry sand.

In the calculation of the German tables the V.D.E. Commission adopted a formula based upon Kennelly's assumption, but took the thermal resistivity of the ground as being one-half the actual value. The reason for this was not apparent until experimental results were obtained which showed that Kennelly's assumptions could not be altogether justified. It may therefore be inferred that the reduced value was taken to meet the discrepancy between calculated and experimental values. As an alternative method of reconciling the two sets of values a formula based on Apt's assumption was also considered. Here in place of Kennelly's assumption that the surface of the ground is an isothermal it is supposed that the isothermal surfaces are concentric with the cable, and that the total effect of the earth around it is somewhat arbitrarily regarded as being equal to that of surrounding the cable with a cylinder of earth, the radius of which is equal to the depth of the cable axis below the surface of the ground.

The cables actually tested when buried direct in the ground cover a very wide range of cable sizes, and have been under observation at different periods of the year and under widely different conditions of soil temperature, resistivity, etc. It therefore becomes possible to compare the experimental values for the whole series with existing values, and to consider the modification of the general formula necessary for the calculation of the current-rating of various sizes and types of cables. For the purpose of the comparison the more important factors, such as the moisture content of the soil, have been determined at frequent intervals and the values corrected to a standard value of thermal resistivity of the soil. Also the thermal constants of all the cables have been fully determined, both when in air and buried in the ground, and the effect of armouring has been investigated.

In order to make an effective comparison not affected by small variables in any particular cable the experimental values have been corrected to a common basis, and those given in Table 32 refer to the following conditions:—

(*a*) The dimensions of the cable are exact.
(*b*) The conductor resistance is of standard value.
(*c*) The thermal resistivity of the dielectric is 550 for cables for pressures above 2 200 volts and 750 for cables for pressures up to and including 2 200 volts.
(*d*) The thermal resistivity of the armouring is 300 (this is the average value of all the cables measured at the N.P.L.).
(*e*) The thermal resistivity of the soil is 120.
(*f*) The value of current is that required for a rise of temperature of the conductor of 50 degrees C.

A comparison with the latest V.D.E. tables is given in Table 32.

There are, however, the following important differences between the two sets of values:

(1) Thermal resistivity of the soil. In the German case this is taken as 50, while in the present investigation the value is 120.
(2) The V.D.E. tables refer to two cables run in the same trench; the distance apart is not stated. For comparison, therefore, the experimental values are given both for one cable and for two laid in the same trench, at 4 in. and 8 in. apart respectively between axes. The thermal resistivity $K$ of the cable is in each case 550, corresponding to 500 when calculated by the uncorrected formula.

In Table 33 a comparison is given of the experimental and calculated values of maximum permissible currents; in the latter the Kennelly and Apt assumptions are both used in each case for two values of $g$.

If an intermediate value of $g = 80$ be taken then on the Kennelly assumption, the values given in Table 34 are obtained. Values based on the Apt assumption are in equally good agreement as a series for one particular depth of laying. But the experimental determination of the effect of depth showed that the Kennelly assumption more nearly represented the facts, and therefore the formula based on this assumption has been used with the necessary corrections.

The agreement between the experimental and the calculated values given in Table 34 was considered to be remarkably good, and proved that the method of calculation used was sufficiently close for all practical purposes. The complete current-loading tables, therefore, were calculated on the Kennelly assumption, corrected in accordance with the experimental results (i.e. by taking $g'$ as two-thirds of $g$).

TABLE 32.

*Currents required to cause a Temperature-rise of 50 deg. C. in Armoured Cables laid Direct in the Ground.*

| Size and Type of Cable | Working Pressure, volts | Current in Amperes for a Rise of 50 deg. C. | | | |
|---|---|---|---|---|---|
| | | Experimental Values corrected to a Common Basis of $g = 120$ | | | V.D.E. Tables, $g = 50$ |
| | | One Cable | Two Cables | | Two Cables in One Trench |
| | | | 4 in. Apart | 8 in. Apart | |
| *All Armoured :* | | | | | |
| 0·1 sq. in. concentric .. | 660 | 280 | 213 | 230 | 282 |
| 0·2 sq. in. concentric .. | 660 | 419 | 318 | 345 | 440 |
| 0·15 sq. in. 3-core .. .. | 3 300 | 295 | 224 | 243 | 331 |
| 0·15 sq. in. 3-core .. .. | 11 000 | 288 | 219 | 237 | 310 |
| 0·15 sq. in. 3-core .. .. | 20 000 | 283 | — | — | — |

TABLE 33.

*Comparison of Experimental and Calculated Values of Maximum Permissible Currents.*

| Size and Type of Cable | Working Pressure | Corrected Experimental Values, $g = 120$ | Calculated Values | | | |
|---|---|---|---|---|---|---|
| | | | $g = 120$ | | $g = 60$ | |
| | | | Kennelly | Apt | Kennelly | Apt |
| *All Armoured :* | volts | amps. | amps. | amps. | amps. | amps. |
| 0·1 sq. in. concentric .. | 660 | 280 | 257 | 273 | 313 | 327 |
| 0·2 sq. in. concentric .. | 660 | 419 | 372 | 395 | 454 | 475 |
| 0·15 sq. in. 3-core .. .. | 3 300 | 295 | 258 | 274 | 308 | 321 |
| 0·15 sq. in. 3-core .. .. | 11 000 | 288 | 257 | 286 | 302 | 314 |
| 0·15 sq. in. 3-core .. .. | 20 000 | 283 | 261 | 276 | 309 | 321 |

TABLE 34.

*Comparison of Experimental and Calculated Values of Maximum Permissible Currents.*

| Size and Type of Cable | Working Pressure | Corrected Experimental Values, $g = 120$ (1) | Calculated Values, $g = 80$ (2) | Ratio (2)/(1) |
|---|---|---|---|---|
| *All Armoured :* | volts | amps. | amps. | |
| 0·1 sq. in. concentric | 660 | 280 | 291 | 1·04 |
| 0·2 sq. in. concentric | 660 | 419 | 421 | 1·00 |
| 0·15 sq. in. 3-core | 3 300 | 295 | 288 | 0·98 |
| 0·15 sq. in. 3-core | 11 000 | 288 | 284 | 0·98 |
| 0·15 sq. in. 3-core | 20 000 | 283 | 289 | 1·02 |
| | | | Mean | 1·00$_4$ |

### (9) THREE-CORE CABLES USED ON THREE-WIRE CIRCUITS.

The possible increase of current when a three-core cable is used on a three-wire circuit, the third conductor carrying the out-of-balance current only, has been considered. It is clear that since any out-of-balance current flowing through the third conductor will reduce that in one of the other two by an equal amount, the balanced-load condition is the least favourable from the point of view of temperature-rise. This condition, therefore, has been assumed in the consideration of the problem.

Actual experiments were made with two three-core cables, one a very large 660-volt cable, and the other a 2 200-volt cable, and it was found that in the first case the ratio of the currents to produce the same temperature-rise of the conductor was 100 to 117. The size of the second cable was 0·25 sq. in., and here the ratio of the currents was 100 to 118. These two cables represent a considerable diversity in the ratio of diameter of conductor to thickness of dielectric and, therefore, it can be fairly assumed that the ratio of currents will hold for all sizes of cables.

A determination of the thermal resistance of a three-core cable with only two cores energized was also made by means of the electrostatic method described before. With two conductors only connected, the third being idle, the capacity of a model corresponding to the dimensions of a cable was 191 $\mu\mu$F, and with the three conductors connected the capacity was 232 $\mu\mu$F; the thermal resistance of a cable under these conditions will be in the ratio of the reciprocals of these two values.

If the method is applicable to such a condition the total power dissipated in the cable for a given temperature-rise should be proportional to the capacities. Taking 100 to 117 as the ratio of the current as determined by experiment, since three conductors are carrying current in the one case and two in the other, the power dissipated corresponds to $(100^2 \times 3)/(117^2 \times 2)$, which is proportional to 91/100. The value obtained for one arrangement of the electrostatic model corresponds to 232/191, which is proportional to 100/82; and the value for the other arrangement of the electrostatic model corresponds to 171/136, which is proportional to 100/80.

Thus there is a discrepancy of about 10 per cent between the two methods, and it would appear that the electrostatic method does not apply when two conductors only are carrying current.

### (10) Four-core Cables.

In the case of four-core cables in which three cores only are energized, the fourth carrying any out-of-balance current, it follows that the values will be very nearly the same as for three-core cables with each core equally loaded. It has been shown by comparison of the heating of a three-core cable with two and three cores energized, that the total power in the cable for a given temperature-rise is only decreased by 10 per cent when two cores are energized.

Apart from the fact that the difference between two and three cores is greater than that between three and four, the basis of comparison is much more extreme, since in the one case the heating of three energized cores is compared with that of two energized cores, while in that now under consideration three cores are always energized, the only difference being the interposition of a fourth core which normally carries little or no current. Since in the extreme case mentioned above the difference was only 10 per cent it may be safely assumed that the rating for a four-core cable will be the same as for a three-core.

An experiment on a length of four-core 0·05 sq. in. 660-volt armoured cable showed that when the four conductors were carrying current the power dissipated for a given temperature-rise was only 3·3 per cent more than when three conductors only were carrying current. This test confirms the conclusion reached that for practical purposes the current-rating of a four-core cable, in which the fourth core carries the out-of-balance current, is the same as that for a corresponding three-core cable.

### (11) Triple-concentric Cables.

In the case of triple-concentric cables used on a three-wire system, and assuming the load to be balanced and carried by the two inner conductors, and taking the thicknesses of the dielectric as specified in B.S.S. No. 7—1922, the current for a given temperature-rise would be 5 per cent less than that for the equivalent size of concentric cable with two conductors only.

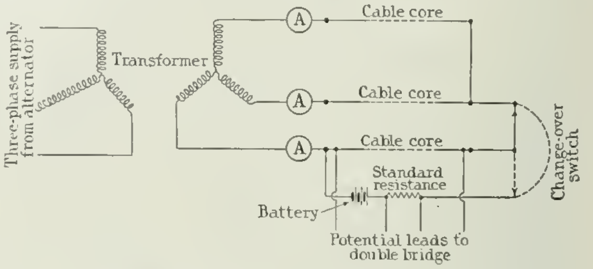


Fig. 14.—Diagram of connections for three-phase loading.

### (12) Cables for Pressures above 11 000 Volts.

It was decided that it would be preferable to defer the preparation of current-loading tables for cables for pressures above 11 000 volts until the complete results of the dielectric-loss tests were available, and that for the present the tables should apply to the sizes and types of cable in general use given in British Standard Specification No. 7—1922.

A great deal of work has been done on cables for pressures above 11 000 volts, but this will form the subject of a further report when this section is completed.

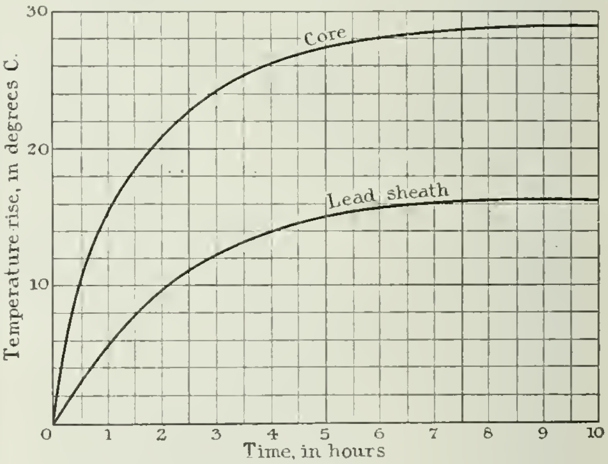


Fig. 15.—Temperature-rise in air of three-core 0·15 sq. in. 20 000-volt cable No. 22, at 200 amperes, three-phase, 25 ∼.

### (13) Comparison between Heating of Three-core Cables with Three-phase Current and Direct Current.

In order to determine whether there is any appreciable increase in the heating of a three-core cable when heated with three-phase alternating current over that observed with an equal direct current, a series of tests has been made on one of the cables (No. 22) as used for 20 000 volts.

The heating current was supplied by three single-phase transformers, connected as shown in Fig. 14. The current in each conductor was carefully balanced by means of a small amount of resistance in the primary circuit of each transformer.

A complete series of observations was taken, as follows :—

(*a*) With the cable lying on the floor with alternating current at a frequency of 50 cycles.
(*b*) The same conditions with alternating current at a frequency of 25 cycles.
(*c*) With the cable supported at intervals at a height of 9 in. above the floor.

The current value was in every case 200 amperes per conductor or per phase.

In order to make a resistance measurement, one conductor was opened temporarily and a direct current of approximately the same value as the alternating current was passed through the cable in series with a standard resistance. The observations in general took about 20 seconds and in no case more than 30 seconds, and the observations showed that even if the direct current were considerably different from the alternating current, this time was too short to cause any appreciable effect on the temperature of the cable.

It will be seen from Fig. 14 that the whole change of connections was made with a simple change-over switch.

Fig. 15 shows the result obtained with the cable supported 9 in. above the floor and loaded with a three-phase alternating current of 200 amperes per phase at a frequency of 25 cycles. This agrees very closely with the previous results on the same cable when tested in air with direct current in 1919, and also with the values now obtained with alternating current at frequencies of 25 cycles and 50 cycles respectively when the cable is laid on the floor. The difference of maximum temperature-rise was in fact less than 1 degree C. for all cases, and if the curves were plotted they would be indistinguishable from one another.

The results show that for cables of this size (0·15 sq. in.) there is no appreciable difference due to three-phase loading, and also dispose of a criticism levelled at the Preliminary Report that there might be a difference between the heating of a cable laid along a floor and when suspended in air.

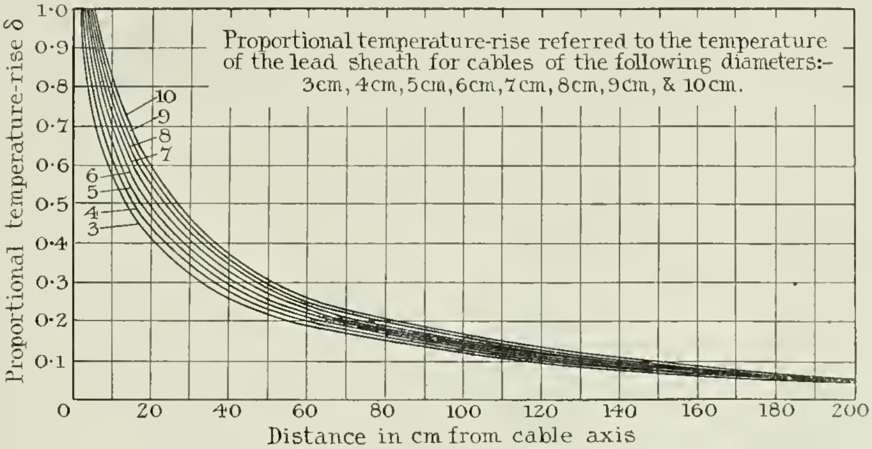


FIG. 16.—Effect due to heating of a neighbouring cable in the same horizontal plane, at a depth below the surface of the ground of 60 cm (2 ft.).

## (14) GROUPED CABLES LAID DIRECT IN THE GROUND.

It will be noted that hitherto only cables laid singly have been dealt with. There are, of course, many cases where several cables are laid near each other in the same trench, and while the widely varying practice in this respect makes it difficult to formulate a general simple rule, a method has been developed for the predetermination of the mutual effect of two or more neighbouring cables.

On Kennelly's assumption (see Teichmüller, "Die Erwärmung der Electrischen Leitungen," p. 55) a buried cable is surrounded by a series of circular eccentric isothermals the depths $y$ of the centres of which below the surface of the ground are given by the formula :—

$$y = \left(\frac{B^2+1}{B^2-1}\right) L \quad . \quad . \quad . \quad . \quad . \quad (39)$$

and the radii $f$ of which are given by the formula :—

$$f = \frac{2LB}{B^2-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

where

$$B = [M + \sqrt{(M^2-1)}]^{\delta} \quad . \quad . \quad . \quad (41)$$

$\delta$ being the ratio of the temperature of the isothermal to that of the surface of the cable, and $M$ the ratio of $L$ to $r_6$, the outer radius of the cable covering.

These equations enable the position and the size of the isothermal circle for any value of the temperature ratio $\delta$ to be calculated and a series of curves to be drawn as shown in Fig. 16. These show the ratio of the temperature-rise to that of the surface of the cable, plotted for any point in a horizontal plane passing through the cable axis. The shape of the curve will vary somewhat with the size of the external diameter of the cable, and therefore a series of curves is required corresponding to various values of the cable diameter. The series given in Fig. 16 applies to cables with external diameters ranging from 3 cm to 10 cm. The axis of the cable is 60 cm (2 ft.) below the surface of the ground in every case.

In order to determine the mutual heating effect of two or more cables, it is necessary to know the diameters of the cables under consideration and $t_4$, the temperature of the outer surface, when the cable is running alone at any specified current. If this is not known from direct measurement, or where, as in the case of armoured cables when buried, direct measurement would be difficult, the temperature of the outside can be obtained if the thermal constants of the cable are known, by means of the equation :—

$$t_4 = t_1 \left( \frac{S_1 + S_2}{S_1 + S_2 + G} \right) \quad . \quad . \quad . \quad . \quad (42)$$

Reference to Fig. 16 will then show the value of $\delta$ for any point in a horizontal plane passing through the axis of the cable, $\delta$ being the ratio of the temperature-rise $t_x$ of that point due to diffusion of heat from the cable compared with the temperature $t_4$ of the outer surface of the cable. A second cable at this point will experience this proportional temperature-rise $\delta$ due to the first cable, in addition to that due to self-heating. The effect of other neighbouring cables can also be calculated and superposed on the first by a repetition of the process. If the permissible temperature-rise of the cable when running alone is $t_1$, and $t_x$ is that due to diffusion from other cables, then the permissible current to a first approximation must be reduced in the ratio

$$\sqrt{\left( \frac{t_1 - t_x}{t_1} \right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

if the permissible temperature-rise is not to be exceeded.

In Tables 35 and 36 and in Fig. 17 the method in its application to the case of several cables is illustrated, and the value of the temperature-rise, as observed by actual experiment when all the cables were running together, has been added for comparison.

For any such case as the experimental one, where the size of the cables and the distance apart will vary, it is necessary to calculate for each condition. The effect of two cables laid in the same trench has, however, been considered and the results are given below

(*a*) *Two cables of the same size and type in the same horizontal plane.*—If two cables of the same size are assumed to be 12 in. (30·5 cm) apart (between centres) the ground temperature, due to mutual influence, varies between 0·30 and 0·45 of the sheath temperature according to the size of the cable (i.e. 3 to 10 cm diameter).

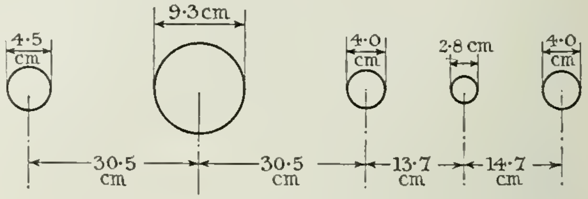


Fig. 17.—Dimensions and relative positions of grouped cables.

Taking $\delta = 0{\cdot}40$ as an average figure (corresponding to a cable of 7 cm diameter), and assuming the temperature-rise of the sheath to be 0·6 of that of the conductor, then if the conductor is 50 degrees C. above datum level, the temperature of the soil at a point 1 ft. distant is as follows :—

$$t_x = 0{\cdot}4 \times 0{\cdot}6 \times 50 = 12$$

$t_x$ being the temperature at a given distance from the cable, and in the same horizontal plane. The temperature of the conductor in a second cable at that point would be raised to 50 + 12 = 62° C. if 50° C. were the temperature the conductor would assume with the first cable cold.

In order then to reduce the temperature-rise of this second cable to 50 degrees C., the currents must be reduced in the ratio $\sqrt{(38/50)} = 0{\cdot}87$.

Table 35.

*Temperature-rise of Cables laid Direct in the Ground and Loaded Singly.**

| Cable .. .. .. .. .. .. .. | A | B | C | D | E |
|---|---|---|---|---|---|
| Load in amps. .. . .. .. .. | 350 | 150 | 220 | 220 | 220 |
| Temperature-rise, deg. C. when running alone at this load | 36·0 inner conductor<br>31·0 outer conductor<br>24·0 sheath | 32·5 conductor<br>32·5 conductor<br>17·5 sheath | 30·5 inner conductor<br>25·3 outer conductor<br>18·5 sheath | 44·8<br>—<br>27·2 | —<br>27·2 conductor<br>12·8 sheath |
| Type and size .. .. .. | 0·2 sq. in concentric | 0·1 sq. in. 6-core | 0·1 sq. in. concentric, armoured | 0·1 sq. in. concentric, lead sheathed | 0·15 sq. in. 3-core |

* The depth below the ground surface was 60 cm (2 ft.) in every case.

TABLE 36.

*Temperature-rise of Cables laid Direct in the Ground as shown in Fig. 17 and when all Cables are Loaded.**

| Diameter, cm .. .. .. .. .. | | 4·5 | 9·3 | 4 | 2·8 | 4 |
|---|---|---|---|---|---|---|
| Proportionate temperature-rise due to the effect of cables given in next column | A | — | 0·35 | 0·20 | 0·15 | 0·12 |
| | B | 0·45 | — | 0·45 | 0·34 | 0·26 |
| | C | 0·19 | 0·35 | — | 0·53 | 0·36 |
| | D | 0·14 | 0·24 | 0·49 | — | 0·48 |
| | E | 0·12 | 0·20 | 0·36 | 0·51 | — |
| Temperature-rise, deg. C., due to effect of cables given in next column | A | 24 sheath † | 8·4 | 4·8 | 3·6 | 2·9 |
| | B | 7·9 | 32·5 conductor | 7·9 | 5·9 | 4·5 |
| | C | 3·5 | 6·5 | 30·5 | 9·8 | 6·6 |
| | D | 3·8 | 6·5 | 13·3 | 44·8 | 13·1 |
| | E | 1·54 | 2·5 | 4·6 | 6·5 | 27·2 |
| Calculated temperature-rise, i.e. sum of above, deg. C. | — | 40·7 | 56·4 | 61·1 | 70·6 | 54·3 |
| Temperature-rise by experiment, deg. C. | — | 39·1 sheath | 54·7 | 58·3 | 71·6 | 54·1 |

* The depth below the ground surface was 60 cm (2 ft.) in every case.
† In this cable only the sheath temperature was available when the cables were run together.

TABLE 37.

*Ratios of Current Reduction due to the Heating of a Neighbouring Cable in the Same Horizontal Plane. Depth of Laying* = 60 *cm* (2 *ft.*).

| Cable | Size of Cable, sq. in. | Working Pressure, volts | $2r_6$ cm | $t_4$ | $\delta$ | $t_x$ | Ratio of Current Reduction | |
|---|---|---|---|---|---|---|---|---|
| | | | | *Separation,* 4 *in.* | | | | |
| A | 0·0225 | 660 | 3·8 | 0·66 | 0·60 | 19·8 | 0·78 | Mean = 0·76 |
| B | 0·0225 | 11 000 | 3·9 | 0·65 | 0·61 | 19·8 | 0·78 | |
| C | 0·25 | 11 000 | 9·0 | 0·57 | 0·78 | 22·4 | 0·74 | |
| D | 0·4 | 660 | 8·9 | 0·61 | 0·77 | 23·5 | 0·73 | |
| | | | | *Separation,* 8 *in.* | | | | |
| A | 0·0225 | 660 | 3·8 | 0·66 | 0·44 | 14·5 | 0·84 | Mean = 0·82 |
| B | 0·0225 | 11 000 | 3·9 | 0·65 | 0·48 | 15·5 | 0·83 | |
| C | 0·25 | 11 000 | 9·0 | 0·57 | 0·56 | 16·0 | 0·82 | |
| D | 0·4 | 660 | 8·9 | 0·61 | 0·56 | 17·0 | 0·81 | |
| | | | | *Separation,* 12 *in.* | | | | |
| A | 0·0225 | 660 | 3·8 | 0·66 | 0·34 | 11·2 | 0·88 | Mean = 0·86 |
| B | 0·0225 | 11 000 | 5·9 | 0·65 | 0·38 | 12·3 | 0·87 | |
| C | 0·25 | 11 000 | 9·0 | 0·57 | 0·44 | 12·6 | 0·86 | |
| D | 0·4 | 660 | 8·9 | 0·61 | 0·44 | 13·4 | 0·85 | |

(*b*) *Calculations for four different sizes of cables in the same horizontal plane.*—Consider a 0·0225 sq. in. 660-volt, three-core cable :

$$2r_6 = 3\cdot82\,;\quad e = 0\cdot34$$

$$\frac{S_1 + S_2}{S_1 + S_2 + G} = \frac{65 + 28\cdot6}{142\cdot8} = \frac{93\cdot6}{142\cdot8} = 0\cdot66 \quad . \ (44)$$

Temperature at a point 1 ft. distant

$$= 0\cdot34 \times 0\cdot66 \times 50 = 11\cdot2$$

Current reduction $\sqrt{(38\cdot8/50)} = 0\cdot882$

And calculating other sizes of three-core cables in the same way for distances of 4 in., 8 in. and 12 in. separation respectively, the results given in Table 37 are obtained.

TABLE 38.

*Ratios of Current Reduction due to the Heating of a Neighbouring Cable in the Same Vertical Plane.*

| $L$ cm | At a Position 12·7 cm (5 in.) above | | | | At a Position 12·7 cm (5 in.) below | | | |
|---|---|---|---|---|---|---|---|---|
| | 45·7 (1 ft. 6 in.) | | 91·4 (3 ft.) | | 45·7 (1 ft. 6 in.) | | 91·4 (3 ft.) | |
| $r_6$ cm | 1 | 4 | 1 | 4 | 1 | 4 | 1 | 4 |
| Ratio of current reduction .. .. | 0·87 | 0·81 | 0·84 | 0·77 | 0·86 | 0·78 | 0·83 | 0·75 |

TABLE 39.

*Tests of Cables in Air, together with a Comparison of Calculated Currents based upon Different Values of Emissivity.*

$h$ = emissivity constant; $K$ = thermal resistivity; $I_1$ = current for a temperature-rise of the conductor of 50 deg. C.

| Size and Type of Cable | Working Pressure | (1) $h$ | (2) $K$ | (3) $I_1$ by Exp. $K = 550$ | (4) $I_1$ by Cal. $h = 0{\cdot}0009$ | (5) $I_1$ by Cal. $h = 0{\cdot}0008$ | (6) Ratio (4)/(3) |
|---|---|---|---|---|---|---|---|
| *Single-core Cables.* | | | | | | | |
| | volts | | | amps. | amps. | amps. | |
| 0·1 sq. in. plain lead .. .. | 660 | — | 1 200 | 263 | 273 | 260 | 1·035 |
| 0·2 sq. in. plain lead .. .. | 660 | — | 800 | 447 | 427 | 412 | 0·955 |
| *Concentric Cables.* | | | | | | | |
| 0·1 sq. in armoured .. .. | 660 | — | 620 | 233 | 245 | 236 | 1·05 |
| 0·2 sq. in. armoured .. .. | 660 | — | 720 | 355 | 385 | 369 | 1·08 |
| 0·2 sq. in. armoured (jute) .. | 660 | 0·00096 | 870 | 367 | 375 | 359 | 1·02 |
| 0·5 sq. in. plain lead .. .. | 2 200 | 0·00083 | 1 090 | 561 | 533 | 512 | 0·96 |
| *Three-core Cables.* | | | | | | | |
| 0·025 sq. in. plain lead (old cable) | Probably 660 | — | 1 050 | 93·5 | 81 | 77·5 | 0·87 |
| 0·05 sq. in. armoured .. .. | 10 000 | 0·0011 | 730 | 142 | 137 | 134 | 0·96 |
| 0·1 sq. in. armoured .. .. | 6 000 | 0·00088 | 420 | 195 | 201 | 198 | 1·03 |
| 0·15 sq. in. segmental conductors armoured .. | 6 600 | 0·00086 | 500 | 251 | 259 | 251 | 1·03 |
| 0·15 sq. in. armoured .. .. | 3 300 | 0·00093 | 608 | 265 | 253 | 245 | 0·95 |
| 0·15 sq. in. armoured .. .. | 11 000 | 0·0010 | 459 | 267 | 267 | 261 | 1·00 |
| 0·15 sq. in. armoured .. .. | 20 000 | 0·0009 | 535 | 275 | 273 | 266 | 0·995 |
| 0·75 sq. in. plain lead .. | 660 | 0·00090 | 750 | 826 | 807 | 775 | 0·98 |
| *Six-core Cable.* | | | | | | | |
| 0·1 sq. in. armoured .. .. | 20 000 | 0·00080 | 600 | 172 | 179 | 174 | 1·04 |

Values of the same order are obtained for different types and sizes of cables, and it is probable that a factor of 0·76 for a pair of cables 4 in. apart, of 0·82 for a pair of cables 8 in. apart, and of 0·86 for a pair 12 in. apart would be sufficiently accurate for all practical purposes.

(*c*) *Calculation of mutual heating effect of two cables laid in the same vertical plane.*—Let the axis of the first be laid at $P_1$ (Fig. 18) and that of another at $P_2$ vertically above it, and $q$ cm distant. If $y$ be the distance below the surface of the ground of the centre of the isothermal circle passing through $P_2$ and $f$ its radius [see Equations (39) and (40)], then

$$y - f = L - q$$

and we have

$$\frac{B-1}{B+1} = 1 - \frac{q}{L}$$

where $B$ has the meaning defined in Equation (41).

But $M^2$ is large in comparison with 1, so that very closely

$$B = \log_e 2M = \log_e (2L/r_6)$$

whence
$$\delta = \frac{\log_e (2L/q - 1)}{\log_e (2L/r_6)} \quad . \quad . \quad . \quad . \quad (45)$$

If the second cable is at $P_2'$ below $P_1$

$$\delta = \frac{\log_e (2L/q + 1)}{\log_e (2L/r_6)} \quad . \quad . \quad . \quad . \quad (46)$$

The calculation of the amount by which the current-rating must be reduced is shown in Table 38 for two values of $L$ and two values of $r_6$, both for the case when the axis of the second cable is 12·7 cm (5 in.) above the first, and also when it is 12·7 cm (5 in.) below.

### (15) CURRENT-RATING OF CABLES IN AIR.

For the purpose of this investigation a large number of different sizes and types of cable have been examined. Tests have been made in every case with the cables laid on the wood floor of a room, and since the values so obtained are useful for purposes of determining the current-rating for cables used under these conditions, a comparison between the experimental and the theoretical values has been made for all the cables tested. The tests carried out on a selected cable supported above the ground in free air gave, within the limits of experimental error, the same results as had been obtained with the same cable laid along a floor free from draughts (see Fig. 15). Thus the results given may be taken as applying equally to either case. The results are given in Table 39.

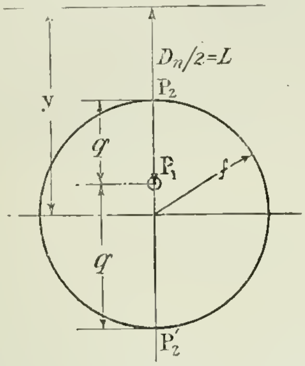


FIG. 18.—Calculation of mutual heating effect of two cables laid in the same vertical plane.

The general method of calculation was the same as that used for buried cables except that the term $G$ is replaced by $A$, the resistance to the flow of heat from the outside surface of the cable to the surrounding air. If $h$ is the emissivity expressed in watts per cm² per degree of temperature-rise of the surface above the surrounding air, then

$$A = \frac{1}{2\pi h r_6} \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

It will be seen that in Table 39, results are included for cables ranging from 0·1 sq. in. single-core to 0·5 sq. in. concentric and cables for various pressures, both plain lead-covered and armoured.

The thermal resistivity constant $K$ has been determined for every case, and all the experimental values have been corrected for $K = 550$.

The emissivity constant $h$ has been determined in the majority of cases and it will be seen that its values range from 0·0008 to 0·0011, depending on the exact nature of the surface of the cable.

Tests made by Mr. J. F. Watson confirm these values very closely. In this case four lengths of cable were tested: (1) with each sheath in its new bright condition, and (2) with each sheath painted a dull black. In the first series the mean value obtained was $h = 0{\cdot}00070$ and in the second $h = 0{\cdot}00107$. Details of these tests are given in Appendix VI. It is probable that the nature of the surface is more important than the colour, and from this point of view Mr. Watson's values probably represent the extremes that can be obtained. In the case of the values given in Table 39 the lead sheath was probably not so bright as that tested by Mr. Watson, and previous tests and observations in other directions indicate that when the sheath has lost its initial brightness the value is nearly the same as with a dull black surface. The same remark applies also to the armoured cables; in one case the value of 0·0011 is nearly identical with Mr. Watson's value for a dull black surface, but in others it is rather lower, depending probably on the nature of the black surface.

For the purposes of calculation, the average value of $h = 0{\cdot}0009$ has been taken, and, in order to show the extent of the difference due to emissivity, a further series of values, using $h = 0{\cdot}0008$, is also given.

### (16) CORRELATION OF RESULTS WITH CABLES IN AIR AND WHEN LAID DIRECT IN THE GROUND.

The values of current required to produce a given temperature-rise with the cables in air can be connected with those required to produce the same temperature-rise when the same cables are laid direct in the ground or drawn into a duct.

It can be shown that the relation between the two values of current required to produce a given temperature-rise under the two conditions is

$$\frac{I_2}{I_1} = \sqrt{\left(\frac{S + A}{S + G}\right)} \quad . \quad . \quad . \quad . \quad . \quad (48)$$

where $A$ = thermal resistance per cm of cable to the flow of heat from the surface of the cable to the air.
$I_1$ = current for a given temperature-rise when the cable is in air.
$I_2$ = current for the same temperature-rise when the cable is laid direct in the ground or drawn into a duct.

This formula enables the heating of a cable laid direct in the ground or drawn into a duct to be deduced from the value obtained when tested in air, and the calculated results are in fair agreement with those derived from experiment. As stated above, however, the emissivity constant $h$ is not easy to determine accurately, and it is probable that a more convenient method would be to make a determination of the total heating of the conductors and the temperature gradient between the conductor or conductors and the sheath by means of observation of the temperature of the lead covering. This also would enable the behaviour of the same cable when buried to be deduced.

The factors for cables drawn into ducts vary, as will be seen from Table 41, from 0·935 to 0·98, a mean value of 0·95 nearly representing all sizes of cables. In the case of armoured cables laid direct in the ground, as would be expected, the values change with varying thickness of dielectric. Actual experiments on cables gave the approximate values shown in Table 40 for the same rise in temperature for each cable in air and when buried direct in the ground.

TABLE 40.

*Current Ratios for Cables when in Air and laid Direct in the Ground at a Depth of 2 ft.,* $g = 90$.

| Type of Cable | Working Pressure, volts | $\frac{I_2}{I_1}$ |
|---|---|---|
| 0·1 sq. in. concentric .. | 660 | 1·22 |
| 0·2 sq. in. concentric .. | 660 | 1·21 |
| 0·15 sq. in. three-core .. | 3 300 | 1·13 |
| 0·15 sq. in. three-core .. | 11 000 | 1·09 |
| 0·15 sq. in. three-core .. | 20 000 | 1·04 |

It should be understood that the correlation refers only to the case where the cable in air is laid out either in free air or along a wood floor free from draughts.

## (17) CURRENT-RATING OF CABLES DRAWN INTO DUCTS.

In the Preliminary Report it was shown (Table 6) that the current required to produce a given temperature-rise when a cable was drawn into a duct was nearly the same as when the same cable was tested in air, and that this applied whatever the relative sizes of cable and duct. A further check has been made by drawing into one of the holes in the duct shown in Fig. 20 the 11 000-volt cable which had previously been tested both when laid in air and direct in the ground. Fig. 19 shows the temperature-rise curves for the three conditions. The ratio of the currents $I_2/I_1$ to produce a given temperature-rise for this cable when in a duct is 0·93.

The full list of the cables for which this ratio was determined, including those given in the Preliminary Report, is given in Table 41.

The values given in Table 41 suggest that the main resistance to the flow of heat is in the layer of air immediately surrounding the cable, and that the relative dimensions of cable and duct and the material of the duct make little difference to the value of the current required to produce a given temperature-rise. The difference in the value of the ratio $I_2/I_1$ between the armoured cable and the others, which were plain lead-sheathed, is probably due to the fact that the emissivity constant of the armoured surface was higher than that of the plain lead, in consequence of which the air condition value for this cable would be higher. The fact that the cable was larger and filled the hole in the duct more completely would appear to have little influence on the results.

Also it seems clear that variation in the resistivity of the surrounding soil will have little effect on the heating of a cable in a duct.

It was decided that current-loading tables should be calculated for one cable drawn into a duct or pipe, the ratio $I_2/I_1$ being taken as 0·95, corresponding to a permissible temperature-rise of 35 deg. C.

TABLE 41.

*Comparison of Current Ratings for Cables in Air and drawn into Ducts.*

| Size and Type of Cable | Working Pressure | External Diameter | $I_2$ | $I_1$ | $\frac{I_2}{I_1}$ |
|---|---|---|---|---|---|
| | volts | in. | amps. | amps. | |
| 0·1 sq. in. concentric .. .. | 660 | $1\frac{1}{16}$ | 130 | 133 | 0·98 |
| 0·2 sq. in. concentric .. .. | 660 | $1\frac{7}{16}$ | 243 | 252 | 0·96 |
| 0·5 sq. in. concentric .. .. | 660 | $2\frac{1}{8}$ | 370 | 378 | 0·98 |
| 0·1 sq. in. three-core .. .. | 660 | $1\frac{1}{4}$ | 157 | 162 | 0·97 |
| 0·1 sq. in. three-core .. .. | Probably 11 000 | $2\frac{1}{4}$ | 162 | 170 | 0·95 |
| 0·15 sq. in. three-core armoured .. | 11 000 | $2\frac{7}{8}$ | 220 | 235 | 0·935 |

$I_1$ = current required to produce a given temperature-rise when the cable is in air.
$I_2$ = current required to produce the same temperature-rise when the cable is drawn into a duct.
Diameter of hole in duct = $3\frac{1}{2}$ in.

## (18) GROUPED CABLES DRAWN INTO DUCTS.

Tests were made to determine the effect of running all the cables in the six-way duct at the same time, and the temperature-rise on two of the cables was measured. The actual arrangement is shown in Fig. 20. The two cables measured were located in holes Nos. 1 and 6. Each cable was a 0·2 sq. in. concentric cable carrying 200 amperes, the power for the length of 100 ft. being approximately 360 watts for each cable. Of the other four cables in the duct, Nos. 2, 3 and 4 were dissipating 165 watts each, and No. 5, 600 watts. Thus the total power in the whole duct when all the cables were running was 1 800 watts per 100 ft. The curves in Fig. 21 show the actual heating of the 0·2 sq. in. cables both when running singly and in a group. It will be noted that the time required to attain to the maximum temperature is somewhat longer when the cables are grouped, and that the temperature-rise is appreciably higher.

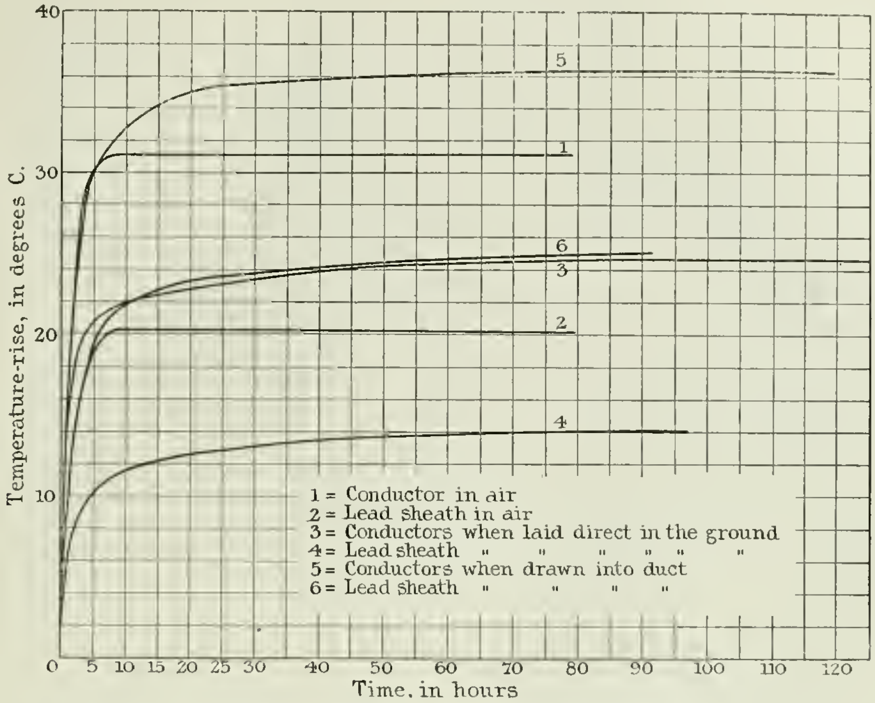


Fig. 19.—Temperature-rise of three-core 0·15 sq. in. 11 000-volt cable laid under different conditions; current = 220 amps.

Values of current calculated from the heating curves in Fig. 21 show that, as a result of grouping, the current must be reduced to 89 per cent of its value when only one cable is carrying current; for a similar cable drawn into the lower hole in the duct the value was 90 per cent. Comparison of the last two values shows that there is no appreciable difference between the upper and lower holes of the duct.

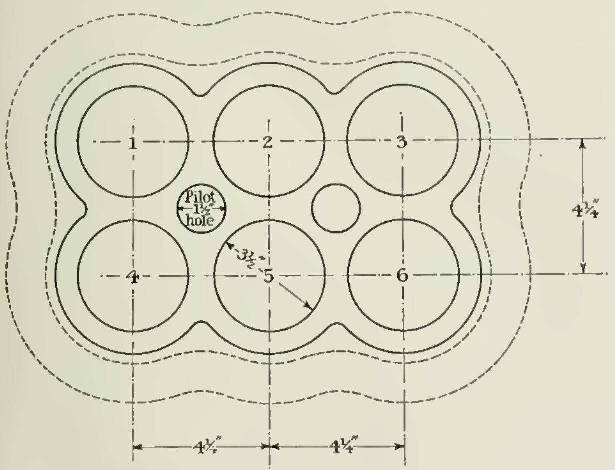


Fig. 20.—Plan of stoneware duct.

### (19) Time required for Cables to attain Maximum Temperature.

The time required for a cable to attain its maximum temperature varies somewhat with the type of cable and the method of laying. In the Preliminary Report it was shown that cables drawn into ducts attained 98 per cent of their maximum temperature in 30 hours, laid solid 92·5 per cent, and laid direct in the ground 91·4 per cent. These values have been fully checked as a result of points raised in the discussion on the Preliminary Report. Taking first the effect of different methods of laying, Fig. 19 shows the curves for an 11 000-volt cable tested at the same current values in air, laid direct in the ground, and drawn into a duct.

It will be seen that in air the cable has attained its maximum temperature in 10 hours, whilst when drawn into a duct it has reached 96·5 per cent of its maximum in 20 hours, and when laid direct in the ground 92 per cent in 20 hours, the maximum temperature in the last case being attained after 5 days. It is, however, most difficult to state the time for maximum temperature accurately, since the rise during the latter portion is very slight and is masked by such factors as fluctuation of ground temperature, small changes of current and limits of error of observation.

Fig. 22 shows the heating curves of cables for various pressures. It will be seen that generally the time required is about 5 days, although for the higher pressure cables it is somewhat shorter and for the cables as used for 20 000 volts probably nearer two to three days. The observations have been extended to cover a period of 15 days, and during the last 9 days of each run there was certainly not a rise of 1 degree C. for the whole of the period, which value is nearly the limit of total error of observation when all the variable factors are taken into account.

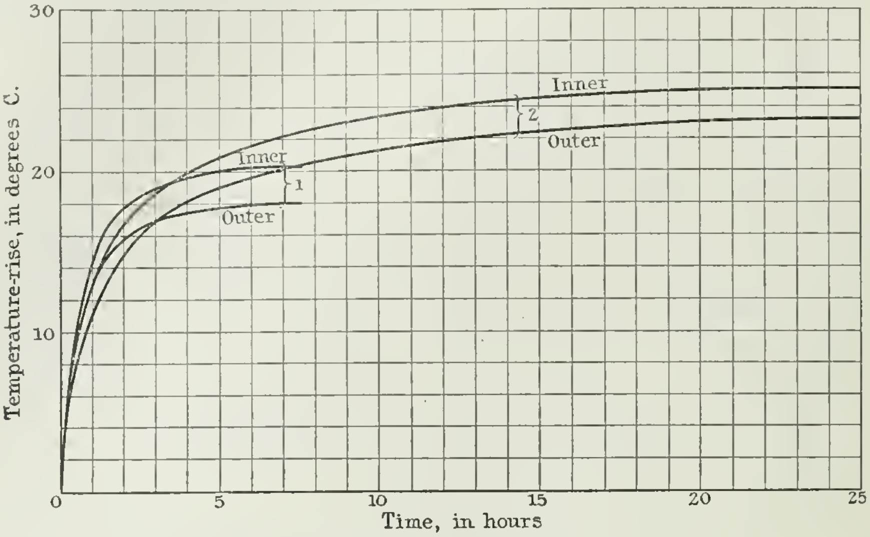


FIG. 21.—Temperature-rise of concentric 0·2 sq. in. 660-volt cable in stoneware duct.

Curves marked 1: one cable only carrying current.
Curves marked 2: six cables carrying current.

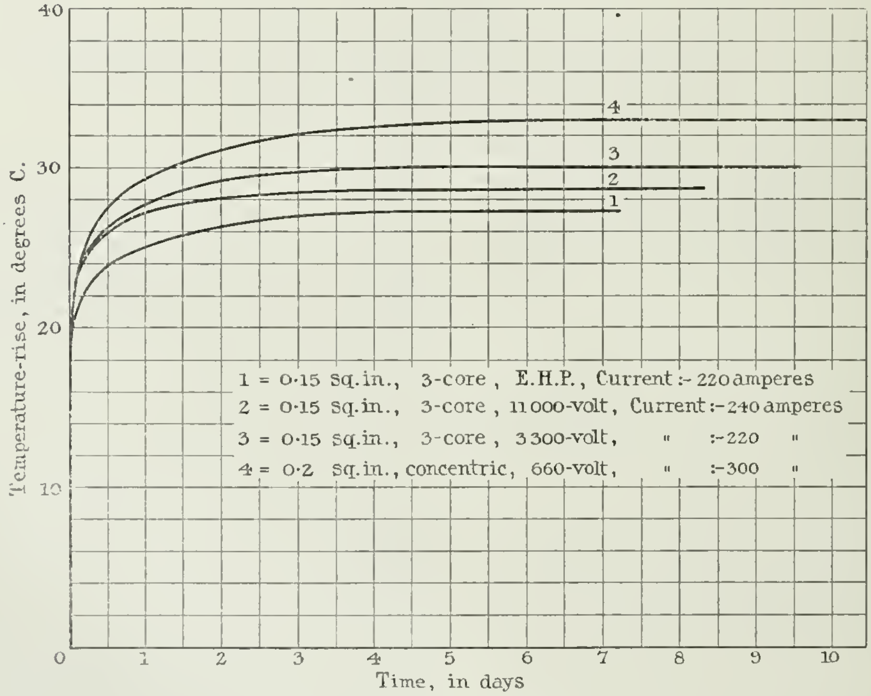


FIG. 22.—Temperature-rise of armoured cables, with various thicknesses of dielectric, laid direct in the ground.

### (20) CURRENT-RATING OF CABLES FOR CYCLICAL INTERMITTENT LOADING.

For cables running in air it is possible to estimate with sufficient accuracy for practical requirements the effect on the current-rating of intermittent or fluctuating loading when regular in character by means of calculations based on the thermal time-constant of the cable involved. This has been fully dealt with in a paper by Messrs. S. W. Melsom and H. C. Booth.*

For cables laid underground it is not possible to find a thermal time-constant and the problem becomes more complicated and does not lend itself so readily to mathematical treatment. The heating and cooling

---

* *Journal I.E.E.*, 1923, vol. 61, p. 363.

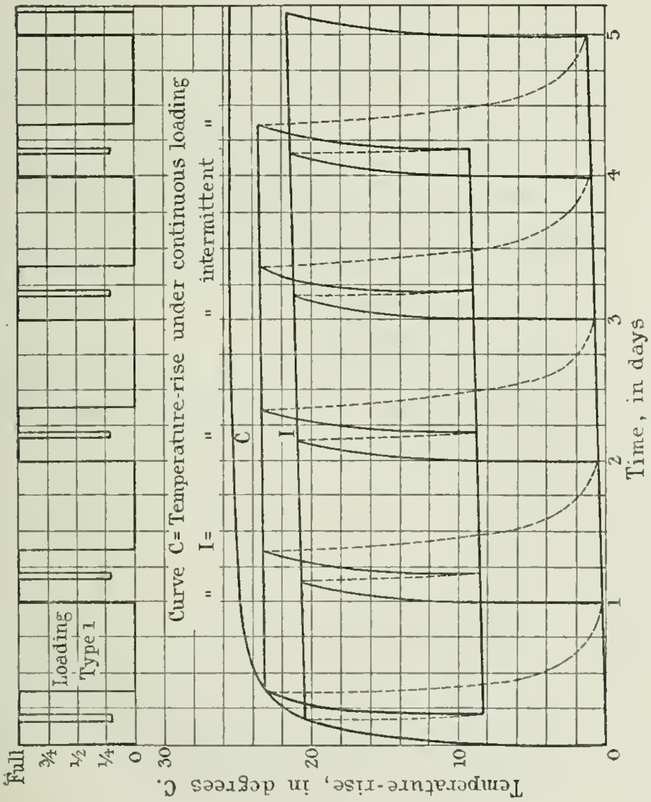


FIG. 23.—Three-core 0·15 sq. in. 20 000-volt armoured cable laid direct in ground; current = 200 amps.

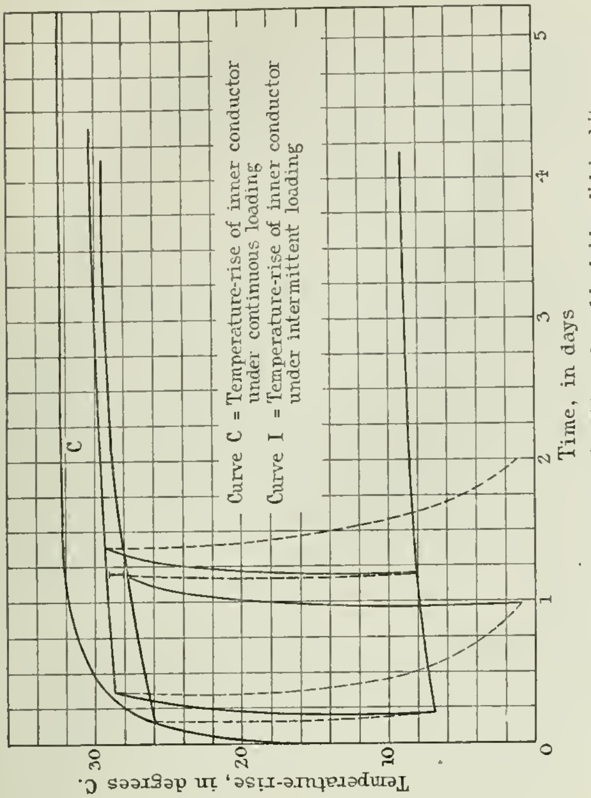


FIG. 24.—Concentric 0·2 sq. in. 660-volt cable laid solid in bitumen; current = 300 amps.; type of loading 1 (Fig. 23).

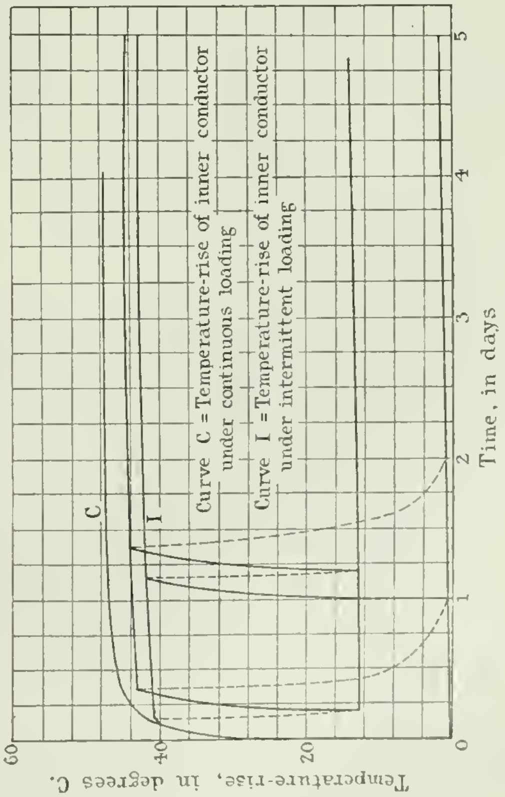


FIG. 25.—Concentric 0·25 sq. in. 660-volt cable in stoneware duct; current = 300 amps.; type of loading 1 (Fig. 23).

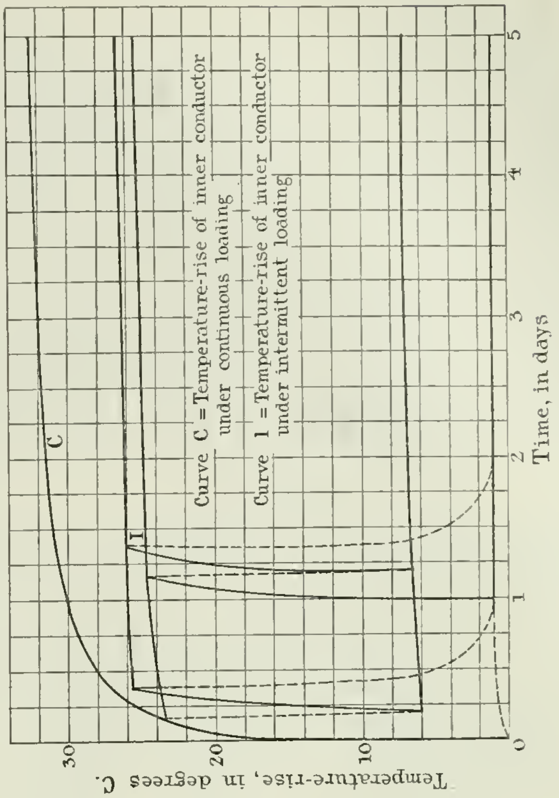


FIG. 26.—Concentric 0·2 sq. in. 660-volt armoured cable laid direct in ground; current = 300 amps.; type of loading 1 (Fig. 23).

curves of cables running in air are found to follow a simple exponential formula fairly closely, since the necessary assumption that the whole of the cable and covering is heated approximately simultaneously by the passage of the current is sufficiently closely justified for the limits of accuracy required. But such a formula does not apply when the same cable is buried, owing to the essentially different conditions that then obtain, for when buried the cable is surrounded by a medium of practically infinite heat capacity through which the heat is slowly diffused.

*Cables laid direct in the ground.*—In view of the difficulty of predetermining values for intermittent loading by means of a thermal time-constant, several tests have been made to determine the additional current, if any, that could be carried by a cable when the loading was more in accordance with the normal load curves of feeder cables.

TABLE 42.

*Current* = 200 *Amperes ; Temperature-rise for Continuous Rating* = 25·5 *degrees C. Type of Loading* (1).

| Time in Intermittent-loading Test | Temperature-rise | Ratio of Currents for the Same Temperature-rise |
|---|---|---|
| | deg. C. | amps. |
| At end of 1st hour .. | 13·5 | 275/200 |
| At end of 2nd hour .. | 17·0 | 245/200 |
| At end of 3rd hour .. | 19·0 | 230/200 |
| At end of 4th hour .. | 20·0 | 224/200 |
| 1 day (9-hour loading) .. | 23·2 | 210/200 |
| 2 days .. .. .. | 23·4 | 209/200 |
| 3 days .. .. .. | 23·5 | 208/200 |
| 4 days .. .. .. | 23·6 | 208/200 |

Four types of loading were dealt with :—

(1) 4 hours at full load.
1 hour at $\frac{1}{5}$ load.
4 hours at full load.
Off for the remainder of the day (corresponding to the loading of a power cable working for a normal 8-hour day).

(2) 2 hours at full load.
1 hour at $\frac{1}{2}$ load.
2 hours at full load.
Remainder of day at $\frac{1}{2}$ load (typical of a combined lighting and power load).

(3) The cables carrying $\frac{1}{2}$ load continuously with peaks to full load of 1, 2, 4 and 8 hours' duration respectively. (To ascertain the extent, if any, by which a cable could be overloaded for short periods.)

(4) The same as (3) but carrying 75 per cent of its normal load continuously.

In all cases the temperature-rise under the intermittent loading is compared with that attained when the maximum load is maintained continuously. For the purpose of this comparison it was necessary to correct the values of the varying thermal resistivity of the soil, and it was more convenient to correct the figures for continuous running than those for the intermittent loads. Thus, although the two sets of values for a particular cable are strictly comparable, they cannot necessarily be compared one cable with another.

(*a*) Type of loading (1) :

A 0·15 sq. in. three-core cable as used for 20 000 volts, armoured, laid direct in the ground. Maximum current = 200 amperes.

The temperature-rise of this cable during the first 4 hours and at the end of the first day, together with the current that could be carried if the cable were used only for periods of from 1 to 4 hours and for one day upwards, are given in Table 42. The complete heating curve is shown in Fig. 23, curve C representing the continuous running condition, and I the intermittent, and the final temperature is given in Table 43.

Three other cables, 0·2 sq. in. 660-volt concentric, laid under different conditions were tested under the same conditions of loading. The results are summarized in Table 43, and are shown in Figs. 24, 25 and 26.

In the curves the actual rate of heating is plotted for the first three days, and after that the upper, intermediate and lower points are shown, joined by a line. The upper curve in each case represents the rise of temperature when the cable is loaded continuously.

Referring to Table 42, at the end of the first hour the temperature-rise was 13·5 degrees C., and if this cable were run for 1-hour periods only with a long interval between the loads, the current for the same temperature-rise as under continuous loading condition could be increased in the ratio of 275/200. After one day with this type of loading the ratio of currents was 210/200, and at the end of five days 208/200. Thus the permissible increase for a normal week's working under these conditions would be only 4 per cent.

Table 43 shows, as would be expected, that the greatest possible overload applies to the 660-volt cable buried direct in the ground. Here the increase is about 10 per cent, but for the other cables it is only of the order of 3 per cent.

(*b*) Type of loading (2) :

For this type of loading the results of the tests on the 660-volt cables are shown in Figs. 27, 28 and 29 and on the cable as used for 20 000 volts in Fig. 30. The results of the tests on all the cables are given in Table 44.

(*c*) Type of loading (3) :

This test has been made only with the cable as used for 20 000 volts, the temperature-rise being shown in Table 45 and in Fig. 31.

(*d*) Type of loading (4) :

The results of tests on a cable as used for 20 000 volts are given in Table 46, and are shown in Fig. 32.

In general, the possible increases of current are not large, although it should be noted that in the case of intermittent loading the maximum temperature is maintained for a short time only, and it is possible that larger currents could be carried for short periods.

The results obtained so far do not justify a recommendation for an increase in the permissible current

TABLE 43.

*Type of Loading* (1).

| Description of Cable and Laying | Temperature-rise after 5½ Days' Running | | Ratio of Currents for the Same Temperature-rise |
|---|---|---|---|
| | Continuous | Intermittent | |
| | deg. C. | deg. C. | amps. |
| 0·2 sq. in concentric, 660-volt, armoured and laid direct in ground | 32·5 | 26·6 | 330/300 |
| 0·2 sq. in. concentric, 660-volt, lead-covered and drawn into a duct | 47·2 | 44·4 | 309/300 |
| 0·2 sq. in. concentric, 660-volt, lead-covered and laid in bitumen | 32·4 | 30·4 | 309/300 |
| 0·15 sq. in. three-core as used for 20 000 volts, armoured, laid direct in ground | 25·5 | 23·7 | 207/200 |

TABLE 44.

*Type of Loading* (2).

| Description of Cable and Laying | Temperature-rise after 5½ Days' Running | | Ratio of Currents for the Same Temperature-rise |
|---|---|---|---|
| | Continuous | Intermittent | |
| | deg. C. | deg. C. | amps. |
| 0·2 sq. in. concentric, 660-volt, armoured and laid direct in ground | 32·5 | 27·5 | 327/300 |
| 0·2 sq. in. concentric, 660-volt, lead-covered and drawn into a duct | 47·2 | 44·8 | 308/300 |
| 0·2 sq. in. concentric, 660-volt, lead-covered and laid in bitumen | 32·4 | 30·1 | 310/300 |
| 0·15 sq. in. three-core as used for 20 000 volts, armoured and laid direct in ground | 27·6 | 22·8 | 242/220 |

TABLE 45.

*Current* = 220 *Amperes ; Temperature-rise for Continuous Running* = 27·4 *deg. C. Type of Loading* (3).

| Hours | Temperature-rise | Ratio of Currents |
|---|---|---|
| | deg. C. | amps. |
| 1 | 18·9 | 265/220 |
| 2 | 21·7 | 248/220 |
| 3 | 23·1 | 240/220 |
| 4 | 24·3 | 234/220 |
| 5 | 24·7 | 231/220 |
| 6 | 24·8 | 231/220 |
| 7 | 24·9 | 230/220 |
| 8 | 25·0 | 230/220 |

TABLE 46.

*Current* = 220 *Amperes ; Temperature-rise for Continuous Running* = 27·4 *deg. C. Type of Loading* (4).

| Hours | Temperature-rise | Ratio of Currents |
|---|---|---|
| | deg. C. | amps. |
| 1 | 22·8 | 240/220 |
| 2 | 24·5 | 232/220 |
| 3 | 25·4 | 228/220 |
| 4 | 25·8 | 226/220 |
| 5 | 26·2 | 225/220 |
| 6 | 26·6 | 223/220 |
| 7 | 26·9 | 222/220 |
| 8 | 27·0 | 221/220 |

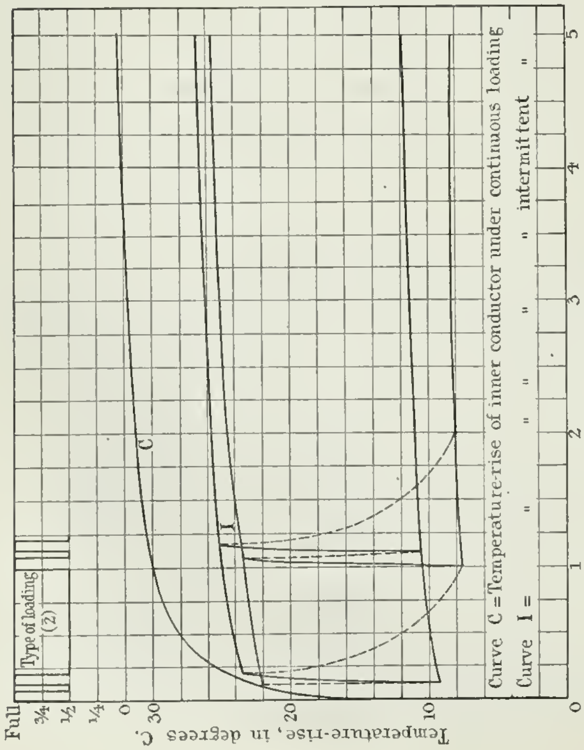


Fig. 27.—Concentric 0·2 sq. in. 660-volt armoured cable laid direct in ground ; current = 300 amps.

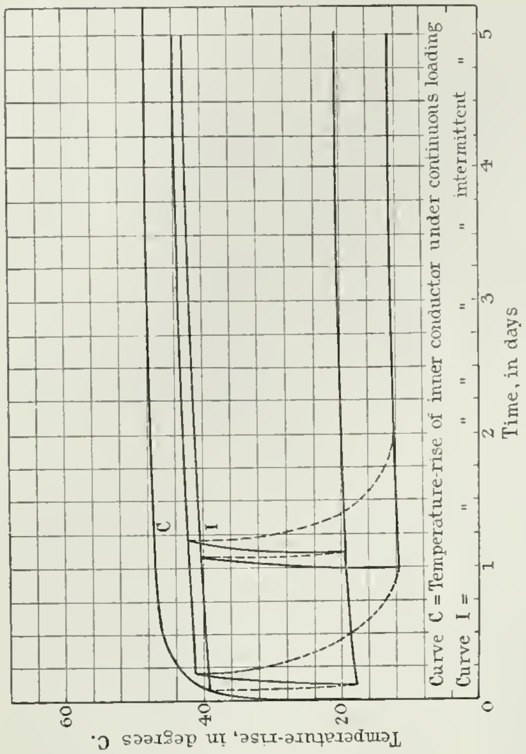


Fig. 28.—Concentric 0·2 sq. in. 660-volt cable in stoneware duct ; current = 300 amps. ; type of loading 2 (Fig. 27).

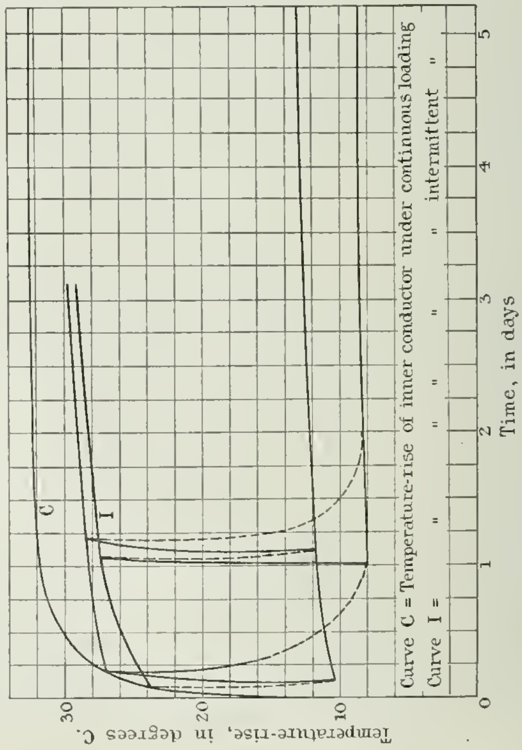


Fig. 29.—Concentric 0·2 sq. in. 660-volt armoured cable laid solid in bitumen ; current = 300 amps. ; type of loading 2 (Fig. 27).

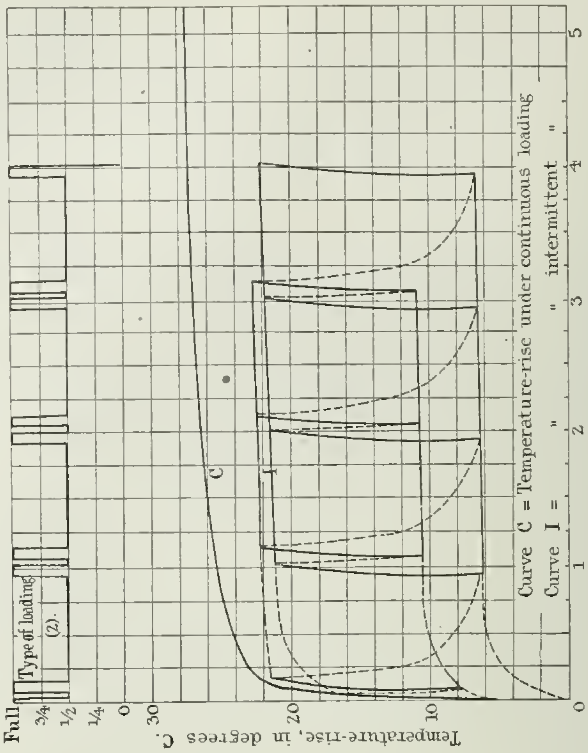


Fig. 30.—Three-core 0·15 sq. in. 20 000-volt armoured cable laid direct in ground ; current = 220 amps.

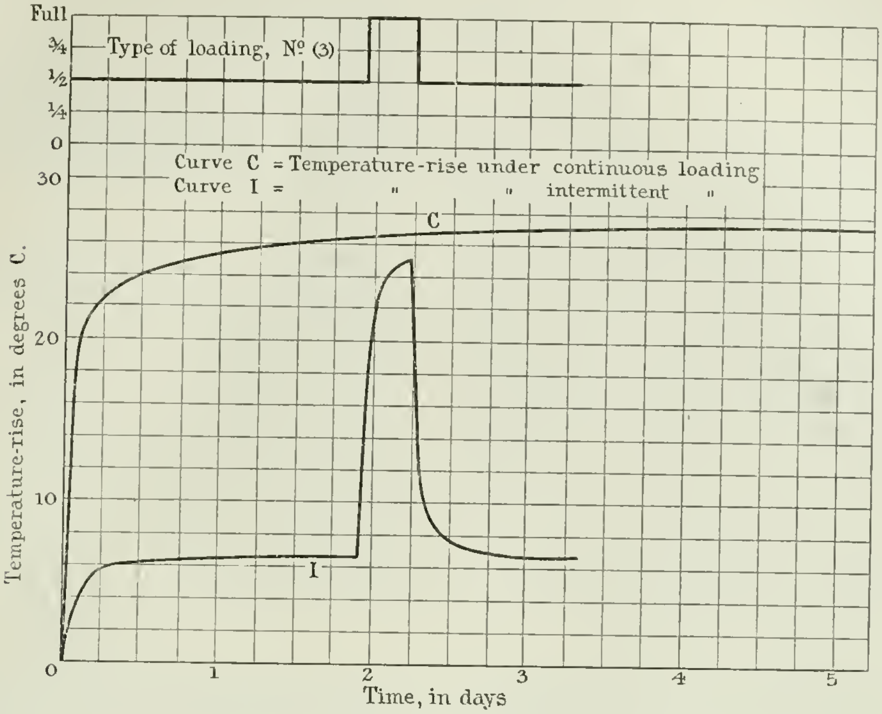


FIG. 31.—Three-core 0·15 sq. in. 20 000-volt armoured cable laid direct in ground; current = 220 amps.

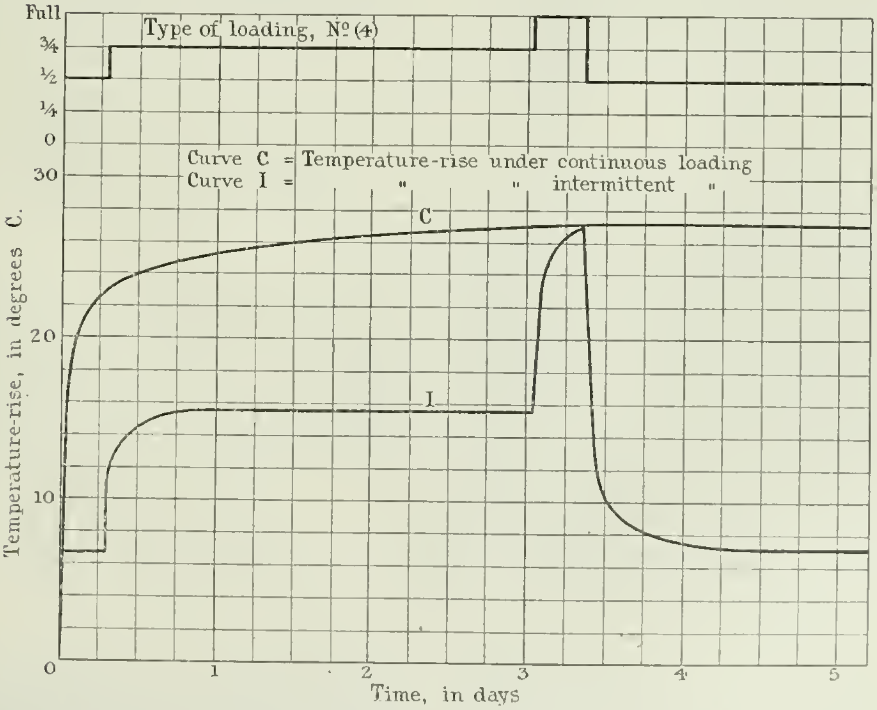


FIG. 32.—Three-core 0·15 sq. in. 20 000-volt armoured cable laid direct in ground; current = 220 amps.

loading for the conditions that have been investigated. Further tests are being made with a type of loading more nearly approximating to that on a traction circuit.

### (21) CURRENT-RATING OF CABLES FOR EMERGENCY LOADING.

A feeder operating at less than full load continuously will carry more than the normal permissible maximum current for a short time without exceeding the specified temperature-rise. In the case of large cables the increment is very considerable if the cable has been previously operating on three-quarters of the normal maximum load or less. A time/temperature-rise curve for the cable laid in the specified manner, between the limits 0 and 50 degrees C. ultimate, called the "characteristic," is all that is required to obtain the permissible emergency load after any known previous steady condition.

Taking the simplest case, as when the cable has not been carrying any load previously, the permissible emergency current is deduced by setting off the emergency time on the "characteristic" starting from zero; then the square root of the ratio that 50 bears to the temperature-rise reached in the short time selected gives the multiplier for that time to apply to the continuous permissible current. Thus, if on the "characteristic" the temperature-rise after one hour is 25 degrees C., the multiplying factor is 1·414, which means that that particular cable laid in that manner will carry, starting from cold, for one hour 41·4 per cent more current than the maximum continuous rating, without exceeding the maximum permissible temperature-rise.

TABLE 47.

*Comparison between the Values of Actual Temperature-rise and those deduced from the Simple Exponential Law.*

| Percentage of Maximum Continuous Current | Final Temperature-rise by Formula (38) | Approximate Rise by Square Law |
|---|---|---|
| per cent | deg. C. | deg. C. |
| 50 | 10·85 | 12·5 |
| 75 | 25·8 | 28·1 |
| 100 | 50·0 | 50·0 |

If the cable has previously been carrying load continuously, the relative temperature-rise for this load is calculable from Formula (38), and this rise is taken as the starting point on the "characteristic." The emergency time is then set off from this point, and the total temperature-rise from zero read off and treated as before, thus giving the multiplying factor for that time under those conditions.

Owing to the cumulative heating effect of the temperature coefficient of copper, the final temperature-rise due to continuous loading is of course not strictly proportional to the square of the current: the comparative values for a maximum temperature-rise of 50 degrees C. are given in Table 47.

The values given in Table 47 of course assume that the thermal resistance outwards from the conductor is constant throughout.

Tests have been made at the National Physical Laboratory on a 0·15 sq. in., three-core, lead-covered and armoured cable, and at Newcastle-upon-Tyne on a 0·35 sq. in. similar cable, in each case laid direct in the ground at a depth of 2 feet, on type of loading (3) referred to in the previous section.

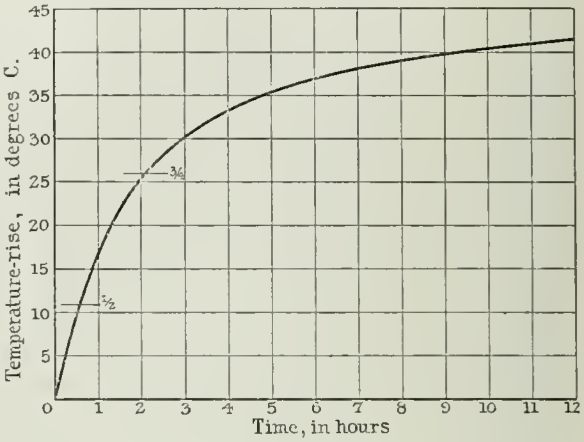


FIG. 33.—Characteristic curve of three-core 0·35 sq. in. 20 000-volt lead-covered and armoured cable laid direct in the ground; ultimate temperature-rise = 50 degrees C.

The Newcastle tests took the following form:—

(*a*) A full-load "characteristic" to give a final temperature-rise of 50 degrees C. in 72 hours. This curve is shown in Fig. 33, and on it are marked the corresponding points 10·85 degrees C. for ½ normal and 26·0 degrees C. for ¾ normal load respectively. From these points 1, 2, 3 and 4 hours were set off and the corresponding total temperature-rises read. These give the multiplying factors to apply to the normal maximum continuous current.

TABLE 48.

*Multiplying Factors to obtain Emergency Current from Maximum Permissible Continuous Rating: Three-core, Lead-covered and Armoured Cable as used for* 20 000 *Volts, laid Direct in the Ground.*

| Size of Cable .. | 0·15 sq. in. | | 0·35 sq. in. | | | |
|---|---|---|---|---|---|---|
| Previous Proportion of Full Load | Half | Three-quarter | None | Half | | Three-quarter |
| | | | | Method (*a*) | Method (*b*) | |
| Emergency Time, hours | | | | | | |
| 1 | 1·205 | 1·097 | 1·74 | 1·48 | 1·46 | 1·28 |
| 2 | 1·125 | 1·057 | 1·40 | 1·32 | 1·316 | 1·225 |
| 3 | 1·09 | 1·04 | 1·285 | 1·254 | 1·252 | 1·187 |
| 4 | 1·06 | 1·03 | 1·22 | 1·20 | 1·22 | 1·162 |

(*b*) After running at a known load till steady, it was doubled and the total rises read at the end of each hour. These give multipliers obtained entirely by test which correspond closely to those calculated for the $\frac{1}{2}$-load condition in (*a*).

(*c*) After running at $\frac{1}{2}$ load till steady, the 1-hour emergency overload (namely, 1·48 times the maximum continuous rating) was applied for exactly one hour, and the total temperature-rise checked out at exactly 50 degrees C.

The values given in Table 48 show that two cables similar in every way except size have very widely different emergency factors. The ratio of capacity for heat (which depends on the area of the complete cable) to radiating surface (which depends on circumference) of course increases largely as the diameter increases, so that the larger cable has naturally a much greater emergency factor.

The thermal time-constant also depends on the specific heat of the materials, the dielectric having a specific heat at least three times that of copper, so that high-voltage cables exhibit a somewhat different characteristic from low-voltage ones. Owing to the many variables involved, a "characteristic" should be taken for each case on which accurate information is sought.

### (22) WORK STILL OUTSTANDING.

Whilst, as will be seen from the report, large sections of the programme have been completed, there are necessarily certain portions of the investigation which are not yet finished. These are :—

(*a*) Cables for pressures above 11 000 volts :

A large amount of work has already been done, but in view of the fact that the determination of the dielectric losses is not yet completed, it was decided to defer the issue of current-loading tables for such cables until all the information is available.

(*b*) Safe maximum temperature :

It has not been possible to make much progress with this section, and therefore it was decided to adopt a maximum temperature for cables for pressures of 11 000 volts and under, which was known to be safe.

(*c*) Three-core cables with segmental conductors :

It is appreciated that these cables are largely used. The determination of the rating depends, however, on the size of the cable and the shape of the segmental conductors. There are no standard dimensions for such cables, and until these are forthcoming it is only possible to give results based on assumed dimensions.

(*d*) Grouping of cables in ducts :

Further work is required to ascertain the effect of running a large number of cables in a multi-way duct.

(*e*) Cables laid on the solid system :

A number of determinations have been made of the thermal resistivity of the compounds used for filling the troughing. The values obtained vary largely, and further investigation is required before current-loading tables can be issued.

### (23) ACKNOWLEDGMENT.

The Research Association desires to express its appreciation of the excellent work of the investigators, Messrs. S. W. Melsom and E. Fawssett, and their assistants, Messrs. H. C. Booth, S. D. Anderson and H. Parry, and of the invaluable assistance of Messrs. J. R. Beard, C. Vernier, J. F. Watson and B. Welbourn, who have collaborated in this research.

The Association is indebted to the Newcastle-upon-Tyne Electric Supply Co., Ltd., for continued co-operation and provision of facilities for the tests carried out in the North-Eastern district ; also to those members of the C.M.A. who have supplied further cables for test.

## ADDENDUM TO THE REPORT.

(*Received 8th May*, 1923.)

It is now understood that the values quoted on page 541 as having been suggested by various American investigators for the maximum permissible temperature for paper-insulated cables do not necessarily refer to continuous loading conditions. Mr. Torchio has pointed out that the figures he suggested refer to a recommendation that the old double, or overload, rating should be again established in the rating of electrical machinery and cables, and for this overload condition the limit of 105° C. to 110° C. was suggested with the proviso that the overload should not exceed 2 hours in duration, with a total duration of less than 10 per cent of the total hours in the year. For continuous rating a temperature of from 85° C. to 90° C. was considered to be the maximum safe limit.

[The Appendixes to the Report will be found on pages 562–579.]

## APPENDIX I.

Table 49.

*Particulars of the Paper-insulated, Lead-covered Cables employed in the Investigation.*

| (1) | (2) | | (3) | (4) | (5) | (6) | (7) | | (8) |
|---|---|---|---|---|---|---|---|---|---|
| Cable No. | Sectional Area | | Type of Cable | Working Pressure | Approx. Length | Armoured | Tested | | Dates of Manufacture (approx.) |
| | Nominal | Actual | | | | | In Air | In Ground | |
| *Single-core Cables.* | | | | | | | | | |
| | sq. in. | sq. in. | | volts | feet | | | | |
| 1 | 0·1 | 0·094 | Single-core | 660 | 110 | No | Yes | Yes | 1916 |
| 2 | 0·2 | 0·196 | Single-core | 660 | 110 | No | Yes | Yes | 1916 |
| *Concentric Cables.* | | | | | | | | | |
| 3 | 0·1 | 0·108 | Concentric | 660 | 110 | Yes | Yes | Yes | 1916 |
| 4 | 0·1 | 0·099 | Concentric | 660 | 110 | No | Yes | Yes | 1916 |
| 5 | 0·1 | 0·100 | Concentric | 660 | 230 | No | Yes | Yes | Old * |
| 6 | 0·2 | 0·192 | Concentric | 660 | 110 | No | Yes | Yes | 1916 |
| 7 | 0·2 | 0·196 | Concentric | 660 | 120 | No | Yes | Yes | 1918 |
| 8 | 0·2 | 0·197 | Concentric (jute insulated) | 660 | 110 | (Jute covered) | Yes | Yes | Old * |
| 9 | 0·2 | 0·205 | Concentric | 660 | 110 | Yes | Yes | Yes | 1916 |
| 10 | 0·5 | 0·480 | Concentric | 660 | 110 | No | Yes | Yes | 1916 |
| *Three-core Cables.* | | | | | | | | | |
| 11 | 0·025 | 0·029 | 3-Core | 660 | 30 | No | Yes | No | Old |
| 12 | 0·05 | 0·048 | 3-Core (segmental conductors) | 11 000 | 51 | Yes | Yes | No | 1916 |
| 13 | 0·1 | 0·105 | 3-Core | 6 600 | 99 | No | Yes | Yes | Old * |
| 14 | 0·1 | 0·100 | 3-Core (segmental conductors) | 660 | 114 | No | Yes | Yes | Old * |
| 15 | 0·1 | 0·101 | 3-Core (segmental conductors) | 6 600 | 30 | Yes | Yes | No | Old * |
| 16 | 0·15 | 0·150 | 3-Core (segmental conductors) | 6 600 | 30 | Yes | Yes | No | 1916 |
| 17 | 0·15 | 0·145 | 3-Core | 20 000 | 50 | Yes | Yes | No | 1919 |
| 18 | 0·15 | 0·145 | 3-Core | 20 000 | 50 | Yes | Yes | No | 1919 |
| 19 | 0·15 | 0·147 | 3-Core | 20 000 | 50 | Yes | Yes | No | 1919 |
| 20 | 0·15 | 0·145 | 3-Core | 20 000 | 50 | Yes | Yes | No | 1919 |
| 21 | 0·15 | 0·144 | 3-Core | 20 000 | 50 | Yes | Yes | No | 1919 |
| 22 | 0·15 | 0·145 | 3-Core | 20 000 | 50 | Yes | Yes | No | 1919 |
| 23 | 0·2 | 0·120 | Nos. 23 to 26 are 3-phase split-conductor cables, each 0·2 sq. in. sect. area per phase<br>6-Core | 20 000 | 66 | Yes | Yes | No | 1919 |
| 24 | 0·2 | 0·116 | 6-Core | 20 000 | 84 | Yes | Yes | No | 1919 |
| 25 | 0·2 | 0·208 | Twin split | 3 300 | 30 | Yes | Yes | No | 1919 |
| 26 | 0·2 | 0·200 | Oval concentric | 20 000 | 72 | Yes | Yes | No | 1919 |
| 27 | 0·25 | 0·250 | 3-Core | 11 000 | 30 | Yes | Yes | No | 1916 |
| 28 | 0·15 | 0·148 | 3-Core | 3 300 | 116 | Yes | Yes | Yes | 1921 |
| 29 | 0·15 | 0·148 | 3-Core | 11 000 | 110 | Yes | Yes | Yes | 1921 |

* Date of manufacture unknown, but prior to 1916.

### Table 50.

*Dimensions of Cables.*

| (1) | (2) | | (3) | | (4) | | (5) | | (6) | | (7) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Thickness of Dielectric | | | | | | | |
| No. | Diameter over Lead | | Thickness of Lead | | Inner Dielectric | | Outer Dielectric | | Between Conductors | | Between Conductor and Lead | |
| | *Single-core Cables.* | | | | | | | | | | | |
| | in. | cm | in. | cm | in. | cm | in. | cm | in. | cm | in. | cm |
| 1 | 0·75 | 1·90 | 0·08 | 0·20 | 0·08 | 0·2 | — | — | — | — | — | — |
| 2 | 0·95 | 2·41 | 0·10 | 0·25 | 0·09 | 0·24 | — | — | — | — | — | — |
| | *Concentric Cables.* | | | | | | | | | | | |
| 3 | 1·14 | 2·89 | 0·13 | 0·33 | 0·08 | 0·2 | 0·08 | 0·2 | — | — | — | — |
| 4 | 1·15 | 2·92 | 0·09 | 0·23 | 0·07 | 0·18 | 0·08 | 0·2 | — | — | — | — |
| 5 | 1·13 | 2·87 | 0·13 | 0·33 | 0·12 | 0·3 | 0·10 | 0·26 | — | — | — | — |
| 6 | 1·37 | 3·48 | 0·11 | 0·27 | 0·14 | 0·35 | 0·08 | 0·20 | — | — | — | — |
| 7 | 1·35 | 3·42 | 0·09 | 0·24 | 0·12 | 0·3 | 0·09 | 0·24 | — | — | — | — |
| 8 | 1·38 | 3·50 | 0·08 | 0·20 | 0·10 | 0·25 | 0·09 | 0·22 | — | — | — | — |
| 9 | 1·30 | 3·30 | 0·10 | 0·25 | 0·07 | 0·18 | 0·09 | 0·24 | — | — | — | — |
| 10 | 1·35 | 3·42 | 0·09 | 0·24 | 0·16 | 0·4 | 0·16 | 0·4 | — | — | — | — |
| | *Three-core Cables.* | | | | | | | | | | | |
| 11 | 0·43 | 2·20 | 0·06 | 0·15 | — | — | — | — | 0·06 | 0·16 | 0·06 | 0·16 |
| 12 | 0·90 | 2·29 | 0·05 | 0·13 | — | — | — | — | 0·31 | 0·8 | 0·31 | 0·8 |
| 13 | 2·23 | 5·66 | 0·11 | 0·28 | — | — | — | — | 0·25 | 0·65 | 0·40 | 1·0 |
| 14 | 1·23 | 3·12 | 0·10 | 0·25 | — | — | — | — | 0·10 | 0·25 | 0·10 | 0·25 |
| 15 | 1·69 | 4·30 | 0·14 | 0·35 | — | — | — | — | 0·24 | 0·6 | 0·24 | 0·6 |
| 16 | 1·81 | 4·60 | 0·10 | 0·25 | — | — | — | — | 0·24 | 0·6 | 0·24 | 0·6 |
| 17 | 2·56 | 6·50 | 0·11 | 0·28 | — | — | — | — | 0·37 | 0·95 | 0·31 | 0·8 |
| 18 | 2·60 | 6·60 | 0·12 | 0·30 | — | — | — | — | 0·40 | 1·0 | 0·28 | 0·7 |
| 19 | 2·52 | 6·40 | 0·16 | 0·40 | — | — | — | — | 0·35 | 0·9 | 0·31 | 0·8 |
| 20 | 2·48 | 6·30 | 0·16 | 0·40 | — | — | — | — | 0·35 | 0·9 | 0·28 | 0·7 |
| 21 | 2·50 | 6·36 | 0·16 | 0·40 | — | — | — | — | 0·37 | 0·95 | 0·35 | 0·9 |
| 22 | 2·40 | 6·08 | 0·12 | 0·30 | — | — | — | — | 0·35 | 0·9 | 0·31 | 0·8 |
| 23 | 3·19 | 8·10 | 0·14 | 0·35 | — | — | — | — | 0·43 | 1·1 | 0·40 | 1·0 |
| 24 | 3·06 | 7·76 | 0·11 | 0·28 | — | — | — | — | 0·40 | 1·0 | 0·40 | 1·0 |
| 25 | 1·83 | 4·64 | 0·13 | 0·32 | — | — | — | — | 0·16 | 0·4 | 0·16 | 0·4 |
| 26 | 3·07 | 7·80 | 0·16 | 0·40 | 0·12 | 0·3 | — | — | 0·40 | 1·0 | 0·40 | 1·0 |
| 27 | 1·95 | 4·96 | 0·11 | 0·28 | — | — | — | — | 0·20 | 0·5 | 0·20 | 0·5 |
| 28 | 1·79 | 4·54 | 0·13 | 0·32 | — | — | — | — | 0·125 | 0·3 | 0·17 | 0·4 |
| 29 | 2·11 | 5·35 | 0·14 | 0·36 | — | — | — | — | 0·275 | 0·7 | 0·20 | 0·5 |

TABLE 51.

*Particulars of Cables tested in Air laid along the Wood Floor of a Room.*

| (1) | (2) | | (3) | (4) | (5) | (6) | | |
|---|---|---|---|---|---|---|---|---|
| Cable No. | Sectional Area | | Type of Cable | Working Pressure | Armoured | Current for a Rise of 50 deg. F. (27·8 deg. C.)* | | |
| | Nominal | Actual | | | | | | |
| | | | *Single-core Cables.* | | | | | |
| | sq. in. | sq. in. | | volts | | amps. | amps. | amps. |
| 1 | 0·1 | 0·094 | Single-core | 660 | No | — | 190 | — |
| 2 | 0·2 | 0·196 | Single-core | 660 | No | — | 304 | — |
| | | | *Concentric Cables.* | | | | | |
| 3 | 0·1 | 0·108 | Concentric | 660 | Yes | 180 | — | 195 |
| 4 | 0·1 | 0·099 | Concentric | 660 | No | 159 | — | 167 |
| 5 | 0·1 | 0·100 | Concentric | 660 | No | 161 | — | 177 |
| 6 | 0·2 | 0·192 | Concentric | 660 | No | 245 | — | 258 |
| 7 | 0·2 | 0·196 | Concentric | 660 | No | 243 | — | 265 |
| 8 | 0·2 | 0·197 | Concentric (jute insulated) | 660 | (Jute covered) | 265 | — | 295 |
| 9 | 0·2 | 0·205 | Concentric | 660 | Yes | 268 | — | 288 |
| 10 | 0·5 | 0·480 | Concentric | 660 | No | 404 | — | 460 |
| | | | *Three-core Cables.* | | | | | |
| 11 | 0·025 | 0·029 | 3-Core | 660 | No | — | 66 | — |
| 12 | 0·05 | 0·048 | 3-Core (segmental conductors) | 11 000 | Yes | — | 100 | — |
| 13 | 0·1 | 0·105 | 3-Core | 6 600 | No | — | 143 | — |
| 14 | 0·1 | 0·100 | 3-Core (segmental conductors) | 660 | No | — | 156 | — |
| 15 | 0·1 | 0·101 | 3-Core (segmental conductors) | 6 600 | Yes | — | 158 | — |
| 16 | 0·15 | 0·150 | 3-Core (segmental conductors) | 6 600 | Yes | — | 195 | — |
| 17 | 0·15 | 0·145 | 3-Core | 20 000 | Yes | — | 208 | — |
| 18 | 0·15 | 0·145 | 3-Core | 20 000 | Yes | — | 204 | — |
| 19 | 0·15 | 0·147 | 3-Core | 20 000 | Yes | — | 219 | — |
| 20 | 0·15 | 0·145 | 3-Core | 20 000 | Yes | — | 208 | — |
| 21 | 0·15 | 0·144 | 3-Core | 20 000 | Yes | — | 208 | — |
| 22 | 0·15 | 0·145 | 3-Core | 20 000 | Yes | — | 195 | — |
| 23 | 0·2 | 0·120 | Nos. 23 to 26 are 3-phase 6-Core | 20 000 | Yes | — | 284 | — |
| 24 | 0·2 | 0·116 | split-conductor cables, 6-Core | 20 000 | Yes | — | 264 | — |
| 25 | 0·2 | 0·208 | each 0·2 sq. in. sect. Twin split | 3 300 | Yes | — | 219 | — |
| 26 | 0·2 | 0·200 | area per phase Oval concentric | 20 000 | Yes | 258 | — | 270 |
| 27 | 0·25 | 0·250 | 3-Core | 11 000 | Yes | — | 255 | — |
| 28 | 0·15 | 0·149 | 3-Core | 3 300 | Yes | — | 194 | — |
| 29 | 0·15 | 0·148 | 3-Core | 11 000 | Yes | — | 211 | — |

---

* In the case of concentric cables, the values are given separately for inner and outer conductors; with three-core cables the values are the mean for the three conductors.

## APPENDIX II.

### Examination of Mie's Formulæ by Mr. S. Butterworth.

In the general case of Mie's formulæ there are $n$ conductors each of radius $r$, the centres of which are situated at equidistant points on the circumference of a circle of radius $a$.

The sheath of radius $r_4$ is concentric with the circle $a$.

If $K$ is the thermal resistivity of the material between the conductors and sheath, $L$ the length of the cables, and $W$ the thermal resistance, then the first formula given by Mie is

$$W = \frac{K}{2\pi nL}\log_e \frac{1 - \alpha\beta + \sqrt{[(1-\alpha^2)(1-\beta^2)]}}{\alpha - \beta} \quad (49)$$

in which $\alpha = \frac{(a+r)^n}{r_4}$ and $\beta = \frac{(a-nr)}{(a+nr)} \times \frac{(a+r)^n}{r_4}$

The second formula is deduced from (47) upon the assumption that the quantity—

$$1 - \alpha\beta + \sqrt{[(1-\alpha^2)(1-\beta^2)]}$$

is never very different from 2, and may be written

$$W = \frac{K}{2\pi nL}\log_e \frac{r_4}{r_1} \quad . \quad . \quad . \quad . \quad . \quad (50)$$

in which $$r_1 = (a+r)n\sqrt{\frac{nr}{a+nr}} \quad . \quad . \quad . \quad . \quad (51)$$

Formula (50) is identical with that for a cable having a single conductor concentric with the sheath in which $r_1$ is the radius of the conductor, so that $r_1$ is the equivalent of the single conductor which would replace the $n$ conductors and give the same thermal resistance between conductor and sheath.

Mie gives the values shown in Table 52 to indicate the agreement of Formulæ (49) and (50).

$W_A$ = value of thermal resistance by Formula (49).
$W_B$ = value of thermal resistance by Formula (50).

$Z = 1 - \alpha\beta + \sqrt{[(1-\alpha^2)(1-\beta^2)]}$, and is equal to 2 when (49) and (50) are in exact agreement.

Table 52.

| No. of Conductors, $n$ | $\frac{r_4}{a}$ | $\frac{a+r}{r_4}$ | $Z$ | $\frac{W_B}{W_A}$ |
|---|---|---|---|---|
| 2 | 2·15 | 0·85 | 1·78 | 1·18 |
| 2 | 2·15 | 0·80 | 1·84 | 1·09 |
| 3 | 2·00 | 0·85 | 1·91 | 1·06 |
| 3 | 2·00 | 0·80 | 1·93 | 1·04 |
| 4 | 1·85 | 0·85 | 1·94 | 1·03 |
| 4 | 1·85 | 0·80 | 1·96 | 1·01 |

*Limitations of formulæ.*—In the method adopted by Mie, the inner isothermal for which Formula (49) holds is not coincident with the surfaces of the separate conductors, but in the case shown in Fig. 34 consists of the wavy dotted curve shown in the figure, and in the case of a three-core cable may adopt one or other of the forms shown in Fig. 35 according to the relative dimensions of conductors and sheath.

Since the isothermal for which Formula (49) is exact always envelops the conductors, the results given by (49) will always be too low. Mie states that when the conditions approximate to that of Fig. 35A, the error tends to vanish because the isothermal is practically coincident with the conductors. Also, when the conductors approach the sheath and have relatively large radii as in Fig. 35D, the error is again small because the lines of heat-flow are practically confined to the region where the isothermal and conductor surfaces are coincident.

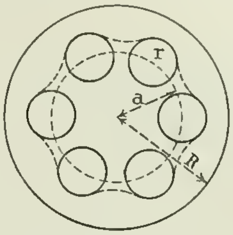


Fig. 34.—Isothermal lines in six-core cable.

By a consideration of the portions of the lines of heat-flow which lie within the isothermal, Mie estimates the maximum error of Formula (49) to be of the order of 5 per cent in the case of a three-core cable.

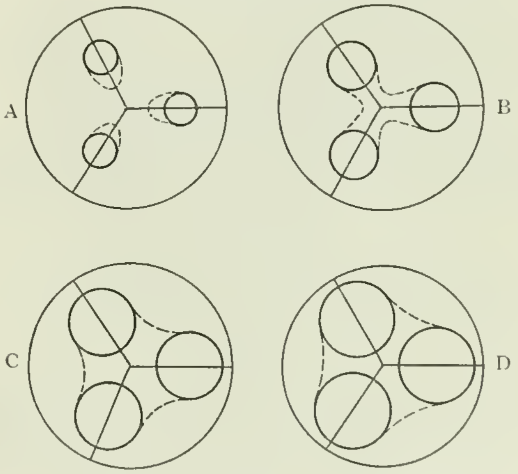


Fig. 35.—Isothermal lines in three-core cable.

It follows, from Table 52, in which Formula (50) is compared with Formula (49), that the error in Formula (50) is less than that indicated by the ratio—$W_B/W_A$, as $W_A$ is itself less than the true thermal resistance, while the ratio $W_B/W_A$ is greater than unity.

There appears to be no reason to doubt the validity of Formula (50) as applied to cables having three or more conductors, if an inaccuracy of 10 per cent is permissible in the results. The inaccuracy of the formula is probably not more than 5 per cent.

## APPENDIX III.

### EXPERIMENTAL DETERMINATION OF THERMAL RESISTANCE BY MEANS OF AN ELECTROSTATIC ANALOGY.

*Thermal resistivity of multi-core cables.*

The analogy may be stated in the form :—

$$4\ (\text{Capacity}) = \frac{\lambda K}{\text{Thermal resistance}} \quad . \quad (52)$$

where $K$ = thermal resistivity, and
$\lambda$ = specific inductive capacity.

If, therefore, a suitable length of metal tube be taken of a size corresponding to the cable sheath, and three or more similar tubes be mounted inside, but electrically insulated from it, in positions corresponding to those of the conductors of a multi-core cable, the apparatus forms a condenser, the capacity of which can be readily determined. By the aid of the relation given above, it then becomes possible to deduce the thermal resistance of the apparatus.

Three cases were tested with the electrostatic model, roughly corresponding to the following three-core cables :—

(1) A cable as used for 20 000 volts.
(2) An 11 000-volt cable.
(3) A 3 300-volt cable.

If $a$ = distance of the centres of the "conductors" from the axis,
$r$ = radius of the "conductors," and
$r_4$ = inner radius of the containing tube,
then the dimensions actual and relative are as given in Table 53.

TABLE 53.

*Dimensions of Electrostatic Model.*

| Case | Dimensions of Electrostatic Model | | | | | |
|---|---|---|---|---|---|---|
| | Actual | | | Relative | | |
| | $a$ | $r$ | $r_4$ | $a$ | $r$ | $r_4$ |
| | cm | cm | cm | | | |
| 1 | 2·12 | 0·73 | 3·64 | 0·58 | 0·20 | 1·00 |
| 2 | 2·04 | 0·96 | 3·64 | 0·56 | 0·263 | 1·00 |
| 3 | 1·695 | 1·28 | 3·64 | 0·46 | 0·351 | 1·00 |

The actual and relative dimensions of the cables referred to above are given in Table 54.

In the capacity tests on the electrostatic models the ratio of the capacity of the three tubes to the outside tube, to that of one of the three tubes placed coaxially to the outside tube, was determined and not the absolute values, which would have necessitated difficult and uncertain corrections for the end effects. The values so obtained were then compared with those obtained by use of each of the formulæ for the ratio derived from Russell's and Mie's formulæ respectively.

The capacity per unit length of two coaxial cylinders of radii $r$ and $r_4$ is

$$\frac{\lambda}{2\log_e(r_4/r)} \quad . \quad . \quad . \quad . \quad . \quad (53)$$

where $\lambda$ = specific inductive capacity.

TABLE 54.

*Dimensions of Three-core* 0·15 *sq. in. Cables.*

| Working Pressure | Dimensions of three 3-core 0·15 sq. in. Cables | | | | | |
|---|---|---|---|---|---|---|
| | Actual | | | Relative | | |
| | $a$ | $r$ | $r_4$ | $a$ | $r$ | $r_4$ |
| volts | cm | cm | cm | | | |
| 20 000 | 1·33 | 0·65 | 2·76 | 0·48 | 0·236 | 1·00 |
| 11 000 | 1·15 | 0·65 | 2·325 | 0·495 | 0·280 | 1·00 |
| 3 300 | 0·90 | 0·65 | 1·95 | 0·463 | 0·334 | 1·00 |

The capacity of three tubes of radius $r$ placed symmetrically at a distance $a$ from the axis of the surrounding tube is, according to Russell,

$$\frac{3\lambda}{2\log_e[(r_4^6 - a^6)/(3r_4^3a^2r)]} \quad . \quad . \quad . \quad (54)$$

Therefore $q_R$, the ratio of the capacities according to Russell, is

$$q_R = \frac{\text{Capacity with 3 eccentric tubes}}{\text{Capacity with 1 coaxial tube}}$$

$$= \frac{3\log_e(r_4/r)}{\log_e[(r_4^6 - a^6)/3r_4^3a^2r]} \quad . \quad . \quad . \quad (55)$$

According to Mie, the capacity of three eccentric tubes is

$$\frac{3\lambda}{2\log_e\left[\left\{(1-\alpha\beta) + \sqrt{(1-\alpha^2)(1-\beta^2)}\right\}/(\alpha-\beta)\right]} \quad (56)$$

where $\alpha = \dfrac{(\alpha + r^3)}{r_4}$ and $\beta = \dfrac{(a - 3r)}{(a + 3r)}\,a$

and therefore $q_M$, the ratio of the capacities according to Mie is

$$q_M = \frac{\text{Capacity with 3 eccentric tubes}}{\text{Capacity with 1 coaxial tube}}$$

$$= \frac{3\log_e(r_4/r)}{\log_e\left[\left\{(1-\alpha\beta) + \sqrt{(1-\alpha^2)(1-\beta^2)}\right\}/(\alpha-\beta)\right]} \quad (57)$$

In Table 55 the following ratios are given for the three cases of the electrostatic model considered :—

(*a*) The ratio of the capacities of one inner to that of three inner tubes by experimental determination, $q$.
(*b*) The ratio of the same capacities determined by the Russell formula, $q_R$.
(*c*) The ratio of the same capacities determined by the Mie formula, $q_M$.

The thermal resistances are proportional to the reciprocals of the capacities of cables of similar dimensions; thus the ratios of the thermal resistances will be the inverse of the ratios of the capacities given above, and the errors will be of opposite sign and must be corrected for numerical value, e.g. minus 29 becoming plus 41 per cent.

TABLE 55.

*Comparison of Ratios determined experimentally and by Russell's and by Mie's Formulæ.*

| Case | $q$ | $q_R$ | $q_M$ | Error of $q_R$ and $q_M$ referred to $q$ | |
|---|---|---|---|---|---|
| | | | | $q_R$ | $q_M$ |
| | | | | per cent | per cent |
| 1 | 3·356 | 3·107 | 3·576 | − 7·5 | + 6·7 |
| 2 | 3·465 | 2·925 | 3·775 | − 15·7 | + 9·0 |
| 3 | 2·975 | 2·11 | 3·335 | − 29·0 | + 12·1 |

In the calculation of thermal resistivity $K$ from a determined value of thermal resistance, the relation assuming Russell's formula is

$$K = \frac{6\pi(t_1 - t_2)}{nl^2 r_4 \log_e\left[(r_4^6 - a^6)/3r_4^3 a^2 r\right]} \quad . \quad . \quad (58)$$

where $t_1$ and $t_2$ are the temperatures of conductor and sheath respectively, and, since the modulus of this expression is usually too great, the value of thermal resistivity determined by means of it is too small.

Hence, taking a cable having an actual thermal resistivity of 500, the values deduced by the two formulæ would be those given in Table 56.

TABLE 56.

*Comparison of Thermal Resistivities of Three-core Cables.*

| Working Pressure | 20 000 V | 11 000 V | 3 300 V |
|---|---|---|---|
| Method | Model (1) | Model (2) | Model (3) |
| By experiment .. | 500 | 500 | 500 |
| By Russell .. .. | 464 | 432 | 388 |
| By Mie .. .. | 533 | 555 | 570 |

Russell's formula is the more convenient and, if the correcting factor be known and applied, values obtained by means of it can be regarded as having a satisfactory degree of accuracy for the higher-pressure cables. In view of its greater simplicity its use was preferred in these cases.

As a result of the experimental work a curve was drawn (see Fig. 36) showing the errors of the Russell formula; it will be seen that for the lower-pressure cables the error appears to become indefinitely large, and for such cases Mie's formula with its smaller error was preferred.

*Effect of the lay on the capacity of the electrostatic model.*—It was suggested by Dr. A. Russell that the lay of the conductors of the cable might have some effect on the thermal resistance, and an experimental determination of the effect of the lay was therefore made with the electrostatic model. Its capacity was measured with three 1·46-cm diameter "conductors" placed at 1·9 cm distance from the axis, and the values for two "conductors" for the following cases are given in Table 57:

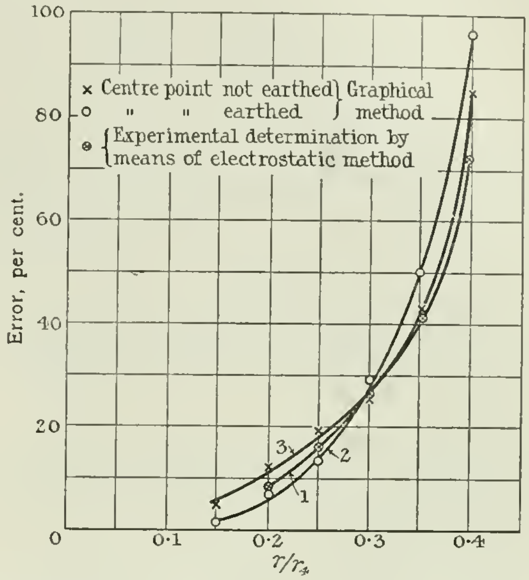


FIG. 36.—Thermal resistance of three-core cable with circular conductors. Error in Russell's formula expressed as a function of the ratio of the radius of the conductor to the inner radius of the lead sheath.

(1) With "conductors" parallel to cable axis.
(2) With one end of the model rotated through 60°, corresponding to a pitch of about 480 cm.

TABLE 57.

*Comparison of Capacities of Electrostatic Model with "Conductors" parallel to Cable Axis and with One End rotated through* 60°.

| Capacity | Case 1 | Case 2 |
|---|---|---|
| Leads + tubes .. .. | 560 | 519 |
| Leads .. .. .. | 86 | 86 |
| Tubes only .. .. | 474 | 433 |

Thus there was a reduction of 8·7 per cent due to the rotation.

The tubes, however, in (2) do not form a true helix, since they remain straight. The effect of the rotation of the ends, therefore, is to cause the centres of the tubes to close in on one another. This fact would in itself reduce the capacity, and the extent of this reduction must be taken into account.

The mean distance of conductor centres from the axis at the ends of the model was 1·87 cm.

At the middle portion of the conductors in the twisted condition the mean distance was, by measurement, 1·61 cm.

The ratio of the capacities for two cases in which $a_1 = 1·87$ and $a_2 = 1·61$ respectively, with $r = 0·73$ and $r_4 = 3·65$, according to the Russell formula,

$$= \frac{\log[(r_4^6 - a_1^6)/3r_4^3 a_1^2 r]}{\log[(r_4^6 - a_2^6)/3r_4^6 a_2^2 r} = \frac{0·9306}{0·7950} \quad . \quad . \quad (59)$$

This minimum distance, however, refers only to the middle portion of the tubes. If, as an approximate assumption, the reduction of capacity is taken as being, therefore, only one-half, this gives 8·5 per cent as the reduction of capacity to be expected on account of the closing in of the middle portions of the tubes, an amount which does not greatly differ from the 8·7 per cent reduction indicated by the experimental determinations. The reduction of capacity in case (2) as compared with (1) is therefore completely explained by the closing-in effect and leaves nothing to be referred to the effect of the lay.

It should be noted that the pitch in the model was about 480 cm, which does not necessarily correspond to the pitch in a cable as manufactured. The experiment, however, does suggest that there is little, if any, difference due to the lay.

## APPENDIX IV.

### Calculation of the Thermal Resistance of Three-core Cables, and Examination of Russell's Formula by Mr. E. B. Wedmore.

The N.P.L. results given in Appendix III cover only a portion of the ground, and with a view to extending the work to cover all cases which may arise, and as a check on previous work, the problem was attacked afresh by a geometrical method described below.

It is shown that the results obtained by the geometrical method are in agreement with those obtained by the experimental tests made. The method has the advantage that it is applicable with equal facility to conductors of any shape, for example, of shapes incapable of simple mathematical expression such as D-shaped and segmental conductors.

The intention is to extend to three-core cables by calculation the results readily obtained for single-core cables. It should be noted, however, that the assumption has been made that the thermal resistivity of the dielectric is the same throughout the section, whereas the material surrounding the cores and next the sheath may differ from that used to pack the odd-shaped spaces between. If, however, this is known to be the case, a correction can be made by the geometrical method but not by any other.

*Geometrical method.*—The method is shown by an example in Fig. 37. The three conductors in the cable are symmetrically placed and therefore it is only necessary to deal with one of them and its sector of 120°. The lines of heat-flow are shown flowing from the conductor to the sheath. The latter is shown by a heavy full line. Isothermals are shown at right angles to the lines of flow.

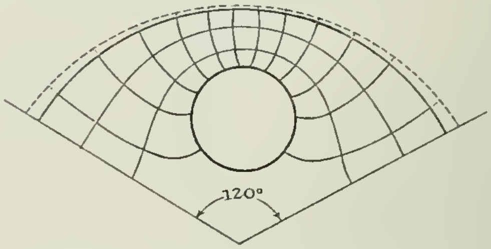


Fig. 37.—Geometrical construction for determining the thermal resistivity of a three-core cable.

The method of construction is as follows :—

(*a*) A certain number is chosen for the lines of heat-flow, in this case 12 per conductor.

(*b*) A rough attempt is made to place these lines and the isothermals, the scale for the isothermals being based on the assumption that the intersections will form squares. This is an arbitrary but convenient scale.

(*c*) The attempt is made and checked on the basis of the following.

  (i) The surfaces of the conductors and sheath respectively are isothermals.

  (ii) The lines of heat-flow must be everywhere at right angles to the isothermals.

  (iii) The intersections must tend to form squares. (Although some of the figures shown are far from square, it will be seen that if intermediate lines of flow and isothermals were inserted they would become more nearly square and, in the limit, the four angles being right angles and the curvature of the sides infinitesimal, they become squares.)

(*d*) A diagram which complies with the above as nearly as can be judged by eye may then be scaled with dividers and an average correction factor worked out. In the case of the diagram shown in Fig. 37, the correction factor worked out at zero, the positive and negative errors cancelling, but in other diagrams a correction of from 1 to 4 per cent was required.

(*e*) The thermal resistivity on the arbitrary scale is shown by the number of isothermals, and to estimate the fraction an imaginary extension is made beyond the sheath to complete the outermost row of squares as shown by the dotted line in Fig. 37. The number is estimated at 2·77, which represents the thermal resistance $x$ between one conductor and the sheath.

(*f*) The corresponding thermal resistance is obtained for a single conductor concentric with the sheath, or may be worked out by the following formula, in which it is assumed that there are 12 lines of heat-flow as in the case considered above.

$$\text{Thermal resistance} = 4 \cdot 40 \log_{10} \frac{r_4}{r} \quad . \quad . \quad (60)$$

(*g*) If the thermal resistivity of part of the dielectric is higher or lower than that of the remainder, the geometrical construction must be modified so that the intersections, instead of being squares, are parallelograms in which the distance between isothermals is proportionately reduced or increased.

*Results obtained.*—The following quantities are used by Mr. Melsom :—

$a$ = distance of centre of conductor from centre of cable.
$r$ = radius of conductor.
$r_4$ = inner radius of sheath.

The thermal resistance is independent of the absolute dimensions and depends only upon the relative values of $a$, $r$ and $r_4$. With $a/r_4 = 0 \cdot 54$, five cases were worked out with different values of $r$, and a sixth, the limiting case, in which, $r/r_4$ being $0 \cdot 46$ and $r/r_4 + a/r_4 = 1$, the conductor touches the sheath. A curve was drawn for this. Three cases were then worked out for each of two other values of $a$, and further curves drawn through these, with the corresponding zero values.

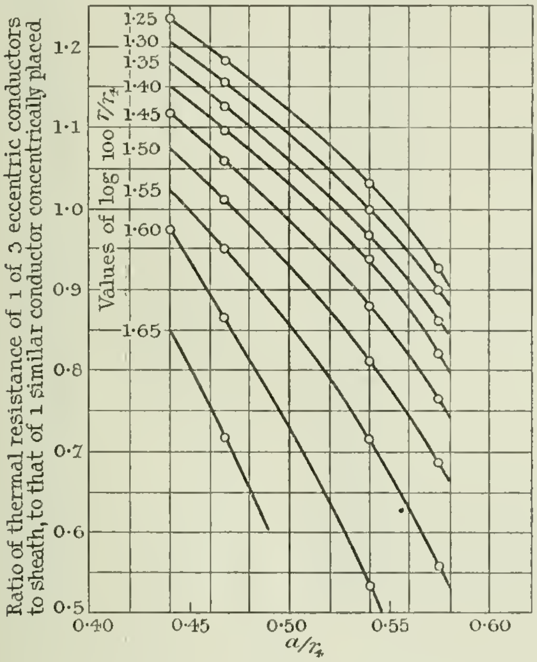


FIG. 38.—Curves for deducing thermal resistances of three-core cables from those of single-core cables.

From these, curves were drawn showing the relationship between the three, from which were finally deduced the curves shown in Fig. 38.

In Fig. 38 the vertical scale gives the ratio between the thermal resistance of one of three eccentric conductors to sheath, to that of a similar conductor concentrically placed. The resistance of three conductors to sheath would be one-third of this.

The horizontal scale gives values of $a/r_4$, and the curves each correspond to a particular value of $\log (100r/r_4)$, which gives a convenient unit, and the values being in equal steps intermediate values are readily obtained by interpolation.

From these curves the thermal resistance of any three-core cable can be worked out from the corresponding thermal resistance of a single-core cable of the same dimensions of sheath and conductor.

*Comparison of results.*—In Table 58 are given the results of calculations of the cases tested by means of capacity measurements, showing the relative values for eccentric and concentric conductors, bearing in mind that the capacities are inversely proportional to the thermal resistances.

TABLE 58.

*Relative Thermal Resistances of Concentric Conductors and Relative Capacities of Eccentric Conductors deduced from the Geometrical Method.*

| Case | Dimensions of Test Pieces | | | $\log \frac{100r}{4}$ | Relative Thermal Resistances, One Conductor, from Curves, Fig. 38 | Relative Capacities, Three Conductors |
|---|---|---|---|---|---|---|
| | $a$ | $r$ | $r_4$ | | | |
| | cm | cm | cm | | | |
| (1) | 0·58 | 0·20 | 1·00 | 1·300 | 0·880 | 3·41 |
| (2) | 0·56 | 0·263 | 1·00 | 1·420 | 0·848 | 3·54 |
| (3) | 0·46 | 0·351 | 1·00 | 1·545 | 0·976 | 3·07 |

In Table 59 is shown a comparison of the relative results from tests made at the N.P.L. and those obtained by the geometrical method.

TABLE 59.

*Comparison between the Results deduced from the Geometrical Method and the Capacity Tests.*

| Case | Geometrical Method (Table 58) (*a*) | Capacity Tests (Appendix 111) (*b*) | Ratio *a*/*b* |
|---|---|---|---|
| (1) | 3·41 | 3·356 | 1·02 |
| (2) | 3·54 | 3·465 | 1·02 |
| (3) | 3·07 | 2·970 | 1·03 |

*Accuracy obtainable.*—In the N.P.L. tests (Appendix 111) there are certain corrections applying to both single-core and concentric cables, such that the series of ratios worked out are probably more accurate than the measurement of the individual capacities. The above results are in conformity with this, and it is thought that the actual figures obtained from the curves here given are at least as accurate as those obtained by the tests made by the electrostatic method.

With any size and form of cable now made, and on the assumption of uniform thermal resistivity of the dielectric and uniform temperature throughout the surface of the conductor, and again of the sheath, one should obtain results correct to within ±2 per cent. If the material used as packing differs in thermal resistivity the error should not be more than 5 per cent with any materials proper for the purpose. These are only estimated figures, but are thought to be safe.

## APPENDIX V.

### TABLE 60.

*Moisture Content of the Soil in the Newcastle-upon-Tyne district.*

| Nature of Soil | Nature of Surface | State of Surface | Date taken | Depth taken | Moisture per cent |
|---|---|---|---|---|---|
| Stiff plastic clay .. .. .. .. | Macadam | Wet | 8/7/20 | 2 ft. 0 in. | 13·7 |
| Brown sandy clay .. .. .. | Macadam | Wet | 8/7/20 | 1 ft. 0 in. | 18·8 |
| Dark brown clay and loam .. .. | Shale | Wet | 11/7/20 | 1 ft. 6 in. | 14·1 |
| Dark brown stiff clay .. .. .. | Shale | Wet | 11/7/20 | 3 ft. 0 in. | 15·2 |
| Dark clay with many small pebbles .. | Macadam | Wet | 15/7/20 | 3 ft. 0 in. | 19·3 |
| Bright red plastic clay with much oxide of iron | Unmade | Wet | 23/7/20 | 7 ft. 0 in. | 44·1 |
| Stiff brown clay and loam .. .. | Grass | Dry | 12/8/20 | 0 ft. 6 in. | 15·1 |
| Brown plastic clay .. .. .. | Grass | Dry | 12/8/20 | 3 ft. 0 in. | 20·9 |
| Cindery soil .. .. .. .. | Macadam | Dry | 22/10/20 | 1 ft. 0 in. | 19·8 |
| Cindery soil .. .. .. .. | Macadam | Dry | 22/10/20 | 2 ft. 0 in. | 21·3 |
| Stiff plastic clay .. .. .. .. | Tarmac | Wet | 9/11/20 | 2 ft. 6 in. | 22·5 |
| Stiff plastic clay .. .. .. .. | Tarmac | Wet | 9/11/20 | 3 ft. 6 in. | 23·0 |
| Loamy with much clay and sand .. | Grass | Dry | 15/11/20 | 1 ft. 3 in. | 23·8 |
| Yellow plastic clay, much sandstone .. | Grass | Dry | 15/11/20 | 2 ft. 6 in. | 25·0 |
| Stiff yellow plastic clay .. .. .. | Grass | Wet | 6/12/20 | 0 ft. 3 in. | 25·3 |
| Soft grey plastic clay with vegetable fibres | Grass | Wet | 6/12/20 | 2 ft. 0 in. | 26·7 |
| Brown clay with much cindery soil .. | Macadam | Wet | 1/12/20 | 2 ft. 0 in. | 18·2 |
| Very soft dark clay .. .. .. | Grass | Wet | 9/12/20 | 5 ft. 6 in. | 33·5 |
| Heavy dark plastic clay .. .. .. | Grass | Wet | 9/12/20 | 9 ft. 0 in. | 38·7 |
| Sand and pebbles .. .. .. .. | Tarmac | Dry | 1/7/21 | 2 ft. 6 in. | 8·8 |
| Stiff yellow plastic clay .. .. | Fine ashes | Dry | 1/7/21 | 1 ft. 8 in. | 21·6 |
| Dark plastic clay and some stones .. | Square sets | Dry | 8/7/21 | 2 ft. 5 in. | 2·5 |
| Stiff brown plastic clay .. .. .. | Macadam | Dry | 26/7/21 | 2 ft. 0 in. | 28·1 |
| Loamy soil with much clay .. .. | Macadam | Dry | 26/7/21 | 1 ft. 0 in. | 12·6 |
| Clayey loam and some cinders .. | Square sets | Dry | 13/7/21 | 2 ft. 6 in. | 16·5 |
| Dark soil, cinders and building refuse .. | Ashes | Dry | 27/7/21 | 0 ft. 6 in. | 8·2 |
| Dark soil, cinders and building refuse .. | Ashes | Dry | 27/7/21 | 2 ft. 0 in. | 12·1 |
| Cindery waste and some clay .. .. | Ash footpath | Damp | 18/8/21 | 0 ft. 6 in. | 19·1 |
| Brown clayey loam .. .. .. | Ash footpath | Damp | 18/8/21 | 1 ft. 6 in. | 15·5 |
| Yellow sand .. .. .. .. | Unmade | Dry | 27/8/21 | 2 ft. 6 in. | 3·8 |
| Yellow sand .. .. .. .. | Grass | Dry | 27/8/21 | 3 ft. 6 in. | 5·5 |

## APPENDIX VI.

### DETERMINATION OF THE EMISSIVITY OF LEAD SHEATHS BY MR. J. F. WATSON.

For the purpose of the tests, four lengths of quite new lead sheath each 9 ft. in length and of varying diameters were obtained. These were mounted singly on a board placed along trestles and raised on blocks of wood 2 in. above the board. The ends were knocked up flat and connections made with the current leads by means of copper bolts. The dimensions of the lead sheaths are given in Table 61.

The sheaths were first tested as received, clean and bright. Care was taken to keep the doors and windows shut during the tests in order to exclude draughts. The results of the tests are given in Table 62.

The lead sheaths were then painted dull black and tested as before. The results of these tests are given in Table 63.

The mean value of the emissivity constant $h$ (watts per degree C. per cm$^2$) for the bright sheath is 0·00070 and for the black sheath 0·00107.

### Table 61.

*Dimensions and Resistance of the Lead Sheaths.*

| No. of Lead Sheath | Total Length | Length between Potential Wires | Diameter over Sheath | Surface Area of Sheath per cm | Thickness of Sheath | Resistance of Sheath | Sectional Area | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Lead Sheath | Copper of Equal Resistance |
| | ft. | ft. | in. | $cm^2$ | in. | ohm | sq. in. | sq. in. |
| 1 | 9 | 6 | 3·30 | 26·30 | 0·170 | 0·00037<br>at 12° C. | 1·74 | 0·133 |
| 2 | 9 | 6 | 1·75 | 14·00 | 0·110 | 0·00110<br>at 20° C. | 0·58 | 0·045 |
| 3 | 9 | 6 | 1·20 | 9·50 | 0·0900 | 0·00180<br>at 20° C. | 0·31 | 0·024 |
| 4 | 9 | 6 | 2·30 | 18·30 | 0·135 | 0·00066<br>at 20° C. | 0·93 | 0·070 |

### Table 62.

*Heating Tests on Bright Lead Sheaths.*

| No. of Lead Sheath | Current | Power Expended | | Temperature | | Calculated Temperature-rise for Uniform *h* | Emissivity Constant, *h* | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Per ft. | Per cm | Starting | Rise | | For Each Test | Mean for Each Test | Mean for Series |
| | amps. | watts | watts | ° C. | deg. C. | deg. C. | | | |
| 1 | 500 | 17·70 | 0·580 | 12·0 | 30·7 | 31·8 | 0·00072 | 0·00069 | 0·00070 |
| | 400 | 10·95 | 0·360 | — | 21·1 | 19·5 | 0·00065 | | |
| | 300 | 6·00 | 0·197 | — | 13·7 | 10·7 | 0·00055 | | |
| | 250 | 4·10 | 0·134 | — | 7·3 | 7·3 | 0·00069 | | |
| 2 | 150 | 4·35 | 0·142 | 20·6 | 13·8 | 14·5 | 0·000734 | 0·000714 | |
| | 125 | 3·00 | 0·098 | — | 10·1 | 10·0 | 0·000692 | | |
| | 100 | 1·88 | 0·062 | — | 6·1 | 6·3 | 0·000734 | | |
| 3 | 80 | 2·06 | 0·068 | 19·2 | 10·0 | 10·2 | 0·000708 | 0·000708 | |
| | 70 | 1·56 | 0·051 | — | 7·6 | 7·7 | 0·000709 | | |
| | 60 | 1·14 | 0·036 | — | 5·3 | 5·4 | — | | |
| 4 | 280 | 9·52 | 0·313 | 20·9 | 24·9 | 24·7 | 0·000680 | 0·00069 | |
| | 240 | 6·88 | 0·225 | — | 18·0 | 17·6 | 0·000683 | | |
| | 200 | 4·65 | 0·153 | — | 11·9 | 11·9 | 0·000700 | | |

### Table 63.

*Heating Tests on Black Lead Sheaths.*

| No. of Lead Sheath | Current | Power Expended | | Temperature | | Calculated Temperature-rise for Uniform *h* | Emissivity Constant, *h* | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Per ft. | Per cm | Starting | Rise | | For Each Test | Mean for Each Test | Mean for Series |
| | amps. | watts | watts | ° C. | deg. C. | deg. C. | | | |
| 1 | 400 | 10·580 | 0·346 | — | 13·7 | 12·0 | 0·00096 | 0·00092 | 0·00107 |
| | 300 | 5·850 | 0·192 | 13·2 | 7·7 | 6·6 | 0·00095 | | |
| | 200 | 2·41 | 0·079 | — | 3·5 | 2·7 | 0·00086 | | |
| 2 | 150 | 4·270 | 0·140 | — | 8·6 | 9·1 | 0·00116 | 0·00112 | |
| | 125 | 2·940 | 0·097 | 19·8 | 6·0 | 6·3 | 0·00115 | | |
| | 100 | 1·870 | 0·061 | — | 4·1 | 4·0 | 0·00106 | | |
| 3 | 120 | 4·740 | 0·155 | — | 14·6 | 14·8 | 0·00112 | 0·00111 | |
| | 80 | 2·030 | 0·067 | 19·0 | 6·3 | 6·4 | 0·00111 | | |
| | 70 | 1·560 | 0·057 | — | 4·8 | 5·0 | 0·00112 | | |
| | 60 | 1·135 | 0·037 | — | 3·6 | 3·6 | 0·00110 | | |
| 4 | 280 | 9·170 | 0·300 | — | 14·5 | 14·7 | 0·00113 | 0·00113 | |
| | 240 | 6·650 | 0·218 | 19·5 | 10·8 | 10·9 | 0·00111 | | |
| | 200 | 4·45 | 0·149 | — | 7·1 | 7·4 | 0·00115 | | |

## APPENDIX VII.

### DETERMINATION OF THERMAL RESISTANCE OF MULTI-CORE CABLES WITH SEGMENTAL CONDUCTORS.

In considering the question of the calculation of the thermal resistivity of three-core cables with segmental conductors, it was found that the construction did not lend itself to mathematical treatment. Experiments were therefore carried out with an electrostatic model somewhat on the same lines as those for three-core cables with circular conductors.

The exact shape of the conductors was not known, but a model was made in accordance with dimensions supplied by Mr. J. F. Watson, with the additional assumption that the overall area (i.e. copper + interstices in the strand) of the segmental conductor was the same as that of the circular conductor. In view of the fact that in some cases the segmental conductors are hammered and rolled, this assumption is not altogether justified, but this does not affect the experimental results appreciably.

Shaped wooden models of a segmental conductor cable corresponding to a 0·25 sq. in. three-core cable were made and covered with tinfoil (see Fig. 39). These were mounted in a brass tube of internal diameter 7·3 cm, and the capacity of the apparatus was measured.

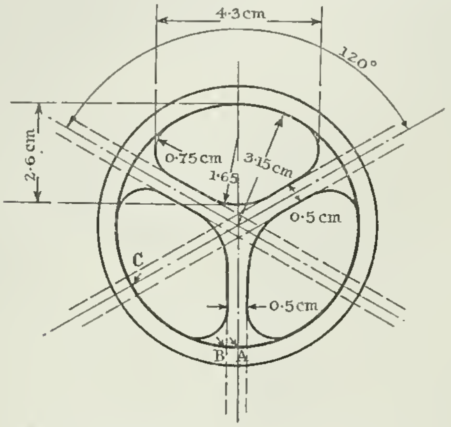


FIG. 39.—Model of three-core cable with segmental conductors, corresponding to a 660-volt cable.

The results were as follows :—

| | |
|---|---|
| Three segments in parallel + leads .. | 320·1 $\mu\mu$F |
| Leads only .. .. .. .. | 17·4 $\mu\mu$F |
| ∴ Three segments only .. .. | 302·7 $\mu\mu$F |

Tinfoil was then wrapped round the three segments whilst still mounted in the position of the previous test so as to form an approximately cylindrical shape enclosing the segments and the capacity was again measured. The results were as follows :—

| | |
|---|---|
| Tinfoil cylinder + leads .. .. | 337·0 $\mu\mu$F |
| Leads only .. .. .. .. | 17·3 $\mu\mu$F |
| ∴ Tinfoil cylinder only .. .. | 319·7 $\mu\mu$F |

Ratio of capacity of segments to that of cylinder $= \frac{302\cdot7}{319\cdot7} = 0\cdot945$.

The effective parts of the segments were assumed to be those directly facing the containing cylinder. The ratio of these (see Fig. 39) was (arc CB)/(arc CA) and this in the model was 12/13 = 0·923.

It therefore follows that the thermal resistance of a cable of this type can be calculated to an accuracy of 2 or 3 per cent by assuming that the heat flows radially from an inner cylinder, except where the three gaps occur, to the outer containing cylinder. The process of calculating the thermal resistance of such a cable would therefore resolve itself into calculating the resistance between the outer cylinder and an inner cylinder which just touched the outer surfaces of the segments, and then increasing the result in the ratio (arc CA)/(arc CB).

The case just considered was a specially favourable one, as the general dimensions corresponded to a 660-volt cable and the gap between the segments was small. The same three shaped segments were therefore mounted in a larger tube of 10·1 cm diameter so as to make the general dimensions correspond to a 6 600-volt cable. The segments were placed so that the distance of the front of the segment from the surrounding cylinder was equal to the distance between the flat sides of the neighbouring segments. With this arrangement, the front circular faces of the segments lay somewhat outside their proper positions (see Fig. 40), but this could have no appreciable effect on the general result. The capacity of the three segments in parallel to the outside containing cylinder was then measured, and the results were as follows :—

| | |
|---|---|
| Segments + leads .. .. | 147·5 $\mu\mu$F |
| Leads only .. .. .. | 17·7 $\mu\mu$F |
| ∴ Segments only .. .. | 129·8 $\mu\mu$F |

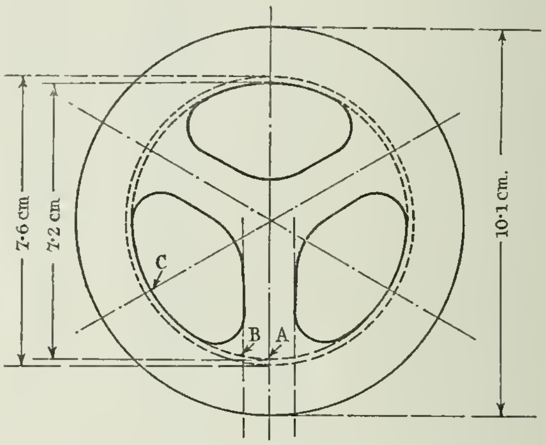


FIG. 40.—Model of three-core cable with segmental conductors, corresponding to a 6 600-volt cable.

Instead of surrounding the segments with tinfoil they were replaced by a brass tube of the same length as the segments and 7·6 cm external diameter. The capacity was then measured and the results were as follows :—

| | |
|---|---|
| Cylinder + leads .. .. | 193·9 $\mu\mu$F |
| Leads only .. .. .. | 17·3 $\mu\mu$F |
| ∴ Cylinder only .. .. | 176·6 $\mu\mu$F |

The cylinder was, however, somewhat larger than a cylindrical surface that would just contain the segments, the diameter of which would be 7·2 cm. The capacity of the apparatus with this cylinder was therefore reduced in the ratio of—

$$\log(10\cdot 1/7\cdot 6) \text{ to } \log(10\cdot 1/7\cdot 2) = 0\cdot 840$$

$$\text{The capacity} = 176\cdot 6 \times 0\cdot 840 = 148\cdot 4$$

$$\text{and the ratio} = 129\cdot 8/148\cdot 4 = 0\cdot 875 = 7/8$$

The ratio of the effective surface of the segments to that of the containing cylinder, namely, (arc CB)/(arc CA) in the second case is 8·7/10·7 = 0·81, and there is a discrepancy of 7·4 per cent between the measured values and those calculated by the proposed rule.

TABLE 64.

*Thermal Resistance of Three-core Armoured Cables laid Direct in the Ground.*

| | 660 volts | | 2 200 Volts | | 3 300 Volts | | 11 000 Volts | |
|---|---|---|---|---|---|---|---|---|
| | Circular Conductors | Segmental Conductors | Circular Conductors | Segmental Conductors | Circular Conductors | Segmental Cooductors | Circular Conductors | Segmental Conductors |
| | | | | *0·25 sq. in.* | | | | |
| $S_1$ | 29 | 17·7 | 34·2 | 23·1 | 24·7 | 17·7 | 37·7 | 34·3 |
| $S_2$ | 17·2 | 20 | 17·6 | 19·1 | 17·2 | 18·5 | 14·0 | 15·7 |
| $G_{10}$ | 41·3 | 42·8 | 40·6 | 42·4 | 49·2 | 50·9 | 46·8 | 48·2 |
| $I_{50}$ | 389 | 402 | 376 | 392 | 374 | 386 | 357 | 361 |
| | | | | *0·1 sq. in.* | | | | |
| $S_1$ | 34·7 | 24·1 | 44·2 | 33·4 | 32·3 | 26·5 | 47·5 | 48·8 |
| $S_2$ | 21·7 | 23·5 | 20·2 | 22·1 | 19·5 | 21·7 | 17·2 | 17·4 |
| $G_{10}$ | 44·8 | 46·3 | 44·0 | 45 | 52·5 | 53·6 | 49·2 | 50·3 |
| $I_{50}$ | 229 | 238 | 222 | 230 | 223 | 229 | 213 | 214 |

$S_1$ = thermal resistance per unit length of cable between conductors and sheath.

$S_2$ = thermal resistance per unit length of cable between the lead sheath and the outer surface of the armouring and protective coverings.

$G_{10}$ = thermal resistance of the soil in this case based on sandy loam having a moisture content of 10 per cent.

$I_{50}$ = current for a temperature-rise of 50 degrees C.

With an 11 000-volt cable the difference would of course be larger, but a method of this kind with the readily obtained correcting factor would be simple and easily applied. The question of exact dimensions is, however, important; there is a large difference between the dimensions of the finished cable supplied by two cable makers, and, further, these do not permit of evaluation of the only dimension which appears to be important for the purpose, i.e. the shape and size of a segmental conductor of a given sectional area. It would appear that there should be no great difficulty in obtaining the necessary dimensions, since the segmental conductor must in practice be rolled or hammered to a given shape, which is as nearly as practicable a segment.

It should be clear that the case given above is most favourable to the method; with smaller conductors and when the proportion of copper to paper is less the correction would probably be larger.

It is useful to consider the amount of possible difference in rating between a segmental and a circular conductor cable, and one or two cases have therefore been worked out for comparison, the value of thermal resistance being based on the method described above.

In view of the absence of standard dimensions for such cables, it was decided that a comparison should be made between three-core cables having circular conductors and those with segmental conductors, on the assumption in the latter case that the conductor and the belt insulation make up a true segment of a circle, thus not allowing for rounding off the conductor. It is clear that this is not a practical case, but a value based on it represents the extreme for this type of cable. The value for an actual cable will lie somewhere between this and that for the corresponding cable with circular conductors, depending on the exact shape of the segmental conductors.

The further assumptions made and the method of calculation are as follows:—

### *General Method of calculating Cables having Segmental Conductors.*

(*a*) The values for cables with segmental conductors are calculated on the assumption that the conductors are true segments having the same overall area of cross-section (i.e. copper plus interstices in the strand) as the corresponding circular conductors.

(*b*) The further assumption is made that the heat flows radially from the circular parts of the segment faces and that there is no flow from the side faces. The thermal resistance of a cable with segmental conductors is thus equal to that of a single-core cable with the same thickness of dielectric, multiplied by a factor which allows for the effect of the three inoperative portions, i.e. multiplying by the factor

$$\theta = \frac{\text{length of arc AC}}{\text{length of arc AB}} \text{ (see Fig. 41)}$$

If $r$ be taken as the radius of the cylinder formed by the three partial conductor segments, and $d$ the overall diameter of the circular conductor of equivalent size,

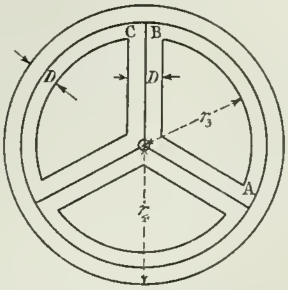


FIG. 41.—Representation of segmental conductor cable.

$$r = \frac{D + \sqrt{(D^2 + 3{\cdot}28d^2)}}{2{\cdot}09} \quad . \quad . \quad (61)$$

$$\text{and the factor } \frac{\text{Arc CA}}{\text{Arc CD}} = \theta = \frac{r}{r + 0{\cdot}77D} \quad . \quad . \quad (62)$$

Eight sizes of cable have been compared and the values of the various components of the thermal resistance are given in Table 64, side by side, in order to facilitate comparison.

The results show that the difference between the current-carrying capacity of cables of the sizes considered, having circular and segmental conductors respectively, is in general negligible, and in the extreme case only about 4 per cent.

## APPENDIX VIII.

### THERMAL RESISTIVITY OF CHALK SOIL.

In view of the large difference between the values of thermal resistivity of sandy loam and clay soils, it was desirable to obtain values for a third type of soil, and tests were made on samples of crushed chalk supplied by Mr. J. Christie. The values obtained are given in Fig. 5 and Table 30. It will be noted that while the value for chalk in the dry condition is higher than that for either gravel or clay, the addition of water results in a series of values intermediate between the other two, the value of 90 with a moisture content of 19 per cent being identical with that of sandy loam with 15 per cent of water.

## APPENDIX IX.

### GRAPHICAL REPRESENTATION OF SELECTED LOAD TABLES.

For the purpose of the preparation of a summary of the report in a form convenient for reading at the meetings of the Institution, a number of the load tables were plotted so that the differences of loading due to the various factors mentioned in the report could be readily appreciated. These are now included in accordance with the request of several members who contributed to the discussion.

Fig. 42 refers to 3 300-volt three-core armoured cables laid direct in the ground, for the four values of thermal resistivity of the soil $g$. The values for the tables published by the Verband Deutscher Electrotechniker are given for comparison. It will be seen that the German values when corrected to the same temperature-rise are somewhat higher than the British ; further, it should be noted that the German values refer to two cables laid in a trench, while the British refer to one cable only. When two cables are laid in one trench at a distance apart of 8 inches, the British values must be reduced to 0·82 of the figures in the curves, and thus the difference between the British and German values would be considerably greater.

Fig. 43 is a similar series of values for an 11 000-volt cable.

The effect of varying thickness of dielectric when cables are laid direct in the ground is shown in Figs. 44 and 45, one set of curves referring to three-core cables with the centre point earthed, and the other not earthed. Fig. 46 gives a similar set of values for concentric cables.

Fig. 47 is a comparison of 660-volt cables, single, concentric and three-core when laid direct in the ground.

Figs. 48 and 49 show the values for concentric and three-core armoured cables when in air, free from draughts. It will be noted that in these cases the order of the curves is not the same as when the cables are buried direct in the ground (see Figs. 44 and 45). The reason is, of course, that in the air condition the increase in thickness of the dielectric in some cases is more than compensated for by the additional radiating surface.

Fig. 50 gives values for 660-volt cables, single, concentric and three-core in air.

Figs. 51, 52, and 53 are curves for three-core cables of different pressures under the three conditions, i.e. in air, buried direct in the ground, and drawn into ducts.

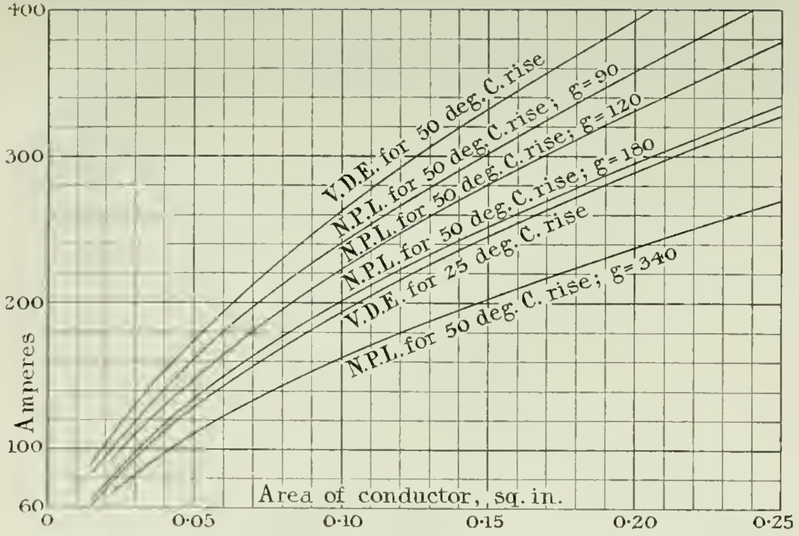


Fig. 42.—3 300-volt 3-core armoured cables laid direct (not earthed).

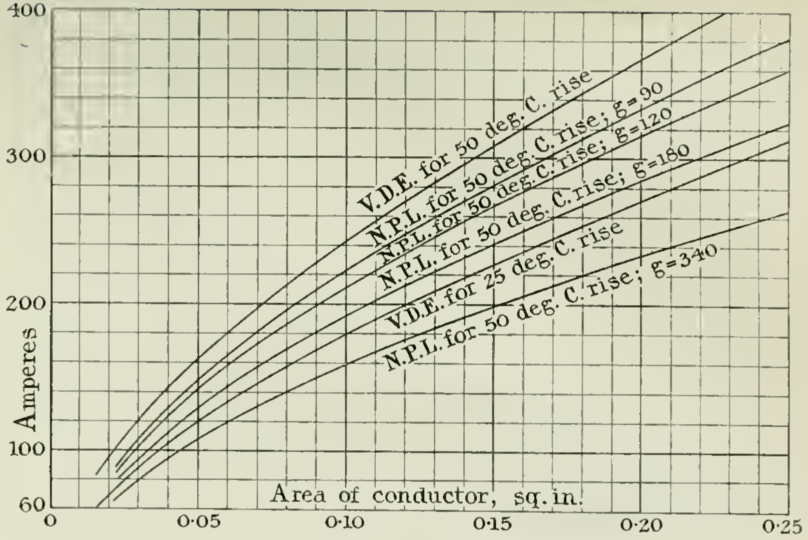


Fig 43.—11 000-volt 3-core armoured cable laid direct (not earthed).

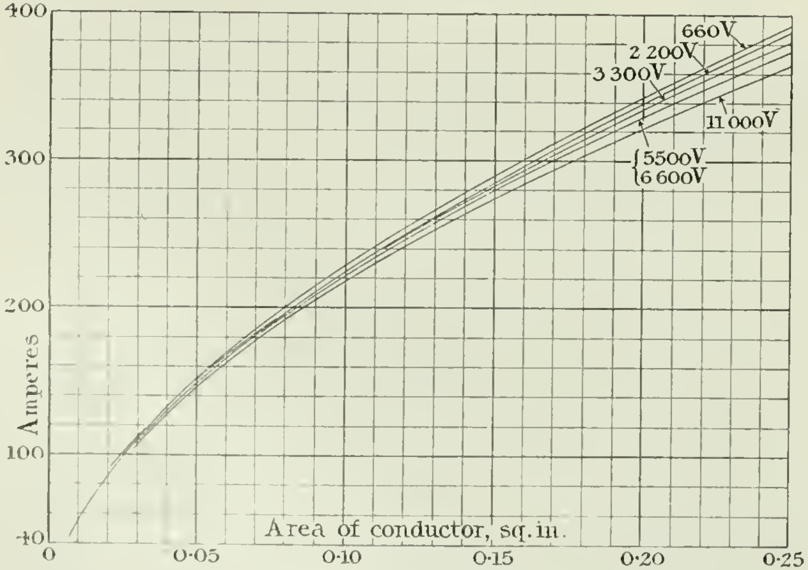


Fig. 44.—Effect of varying thicknesses of insulation of 3-core armoured cables laid direct (earthed). $g = 120$.

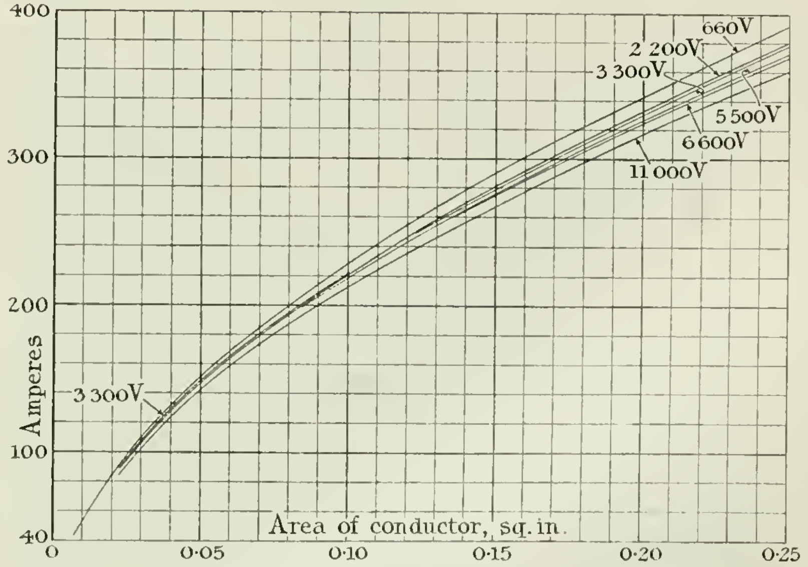


Fig. 45.—Effect of varying thicknesses of insulation of 3-core armoured cables laid direct (not earthed). $g = 120$.

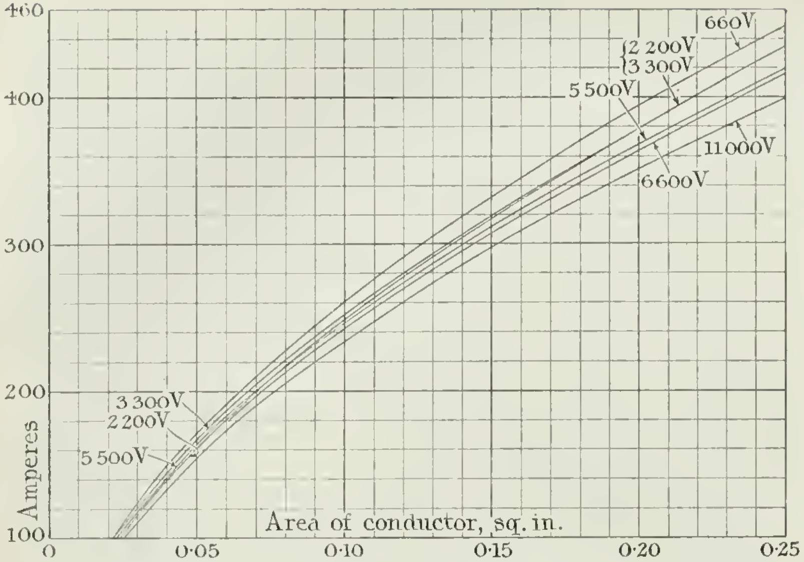


Fig. 46.—Effect of varying thicknesses of insulation of armoured concentric cables (not earthed). $g = 120$.

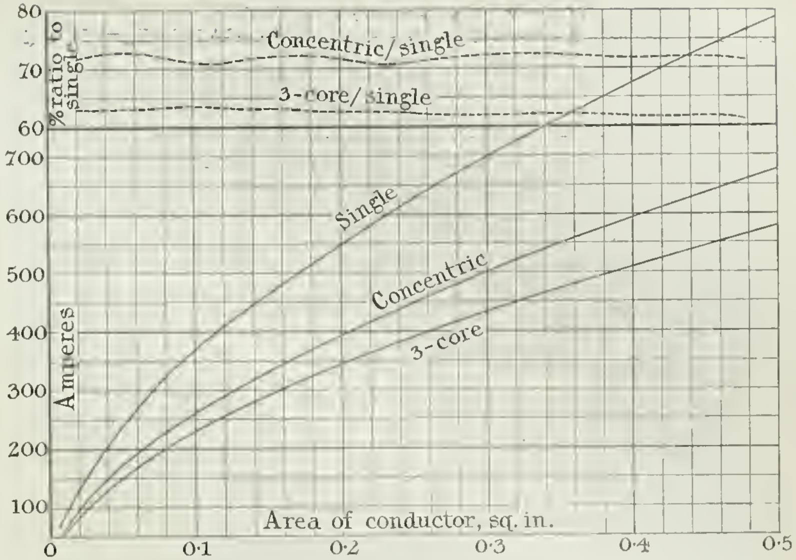


Fig. 47.—Comparison of 660-volt cables, single, concentric and 3-core armoured and buried direct (not earthed), $g = 120$.

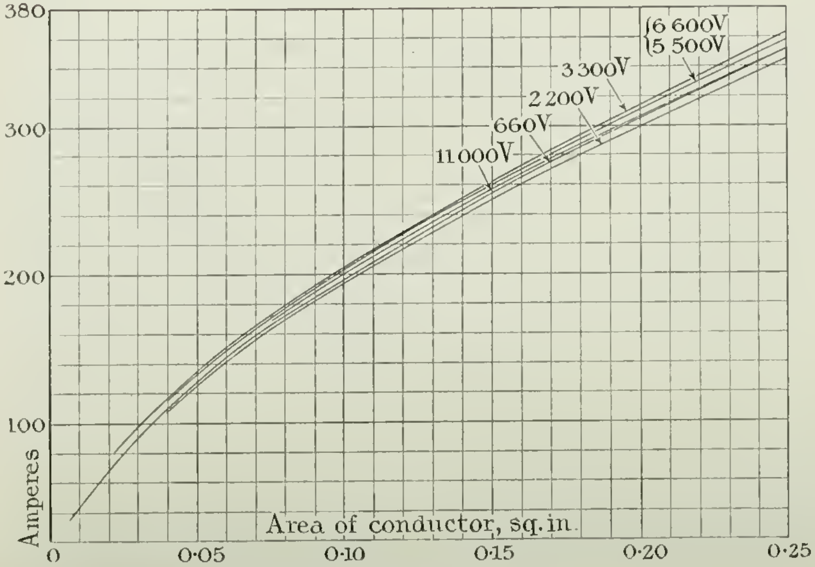


Fig. 48.—Concentric armoured cables in air, at various voltages.

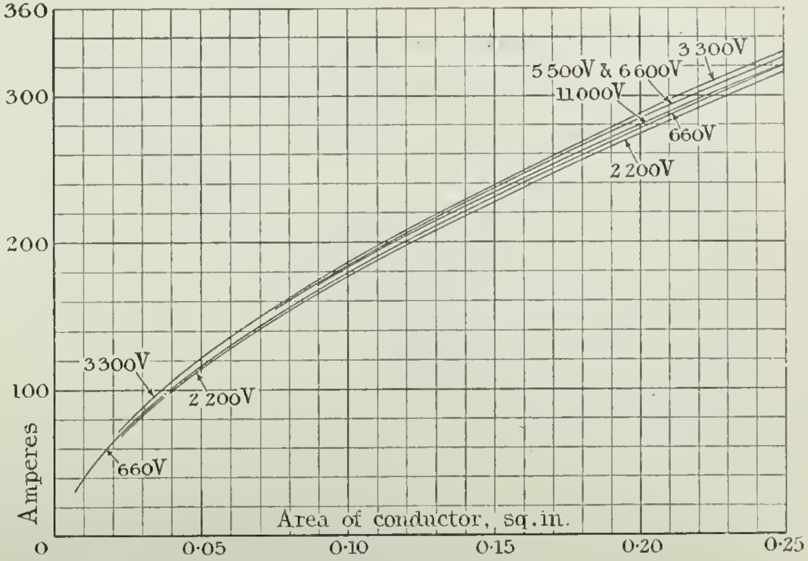


Fig. 49.—3-core armoured cables in air, at various voltages.

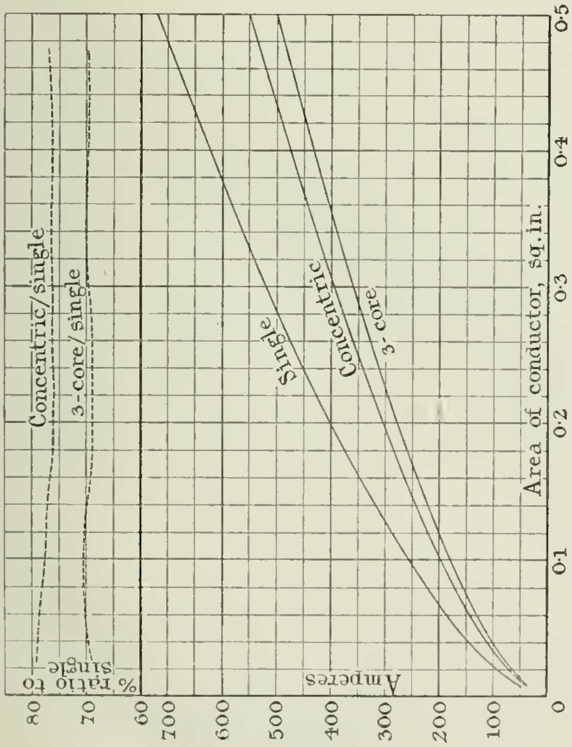


FIG. 50.—Comparison of 660-volt cables, single, concentric and 3-core in air.

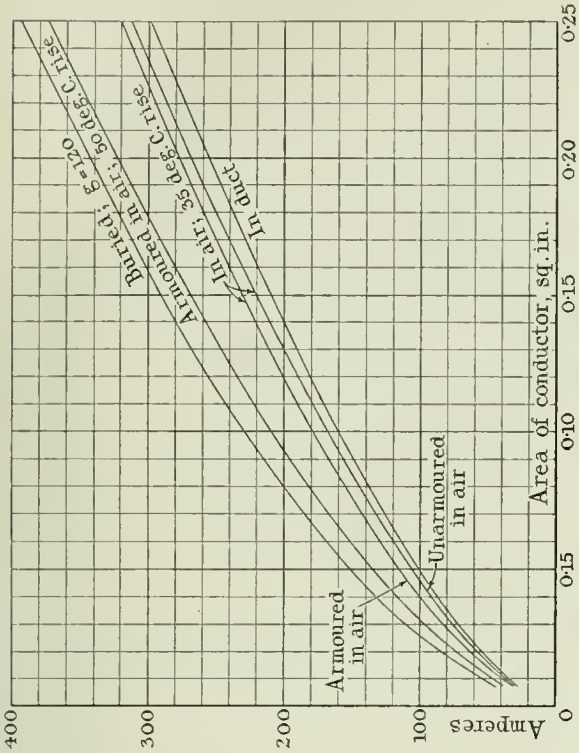


FIG. 51.—660-volt 3-core cables under different conditions of laying (not earthed).

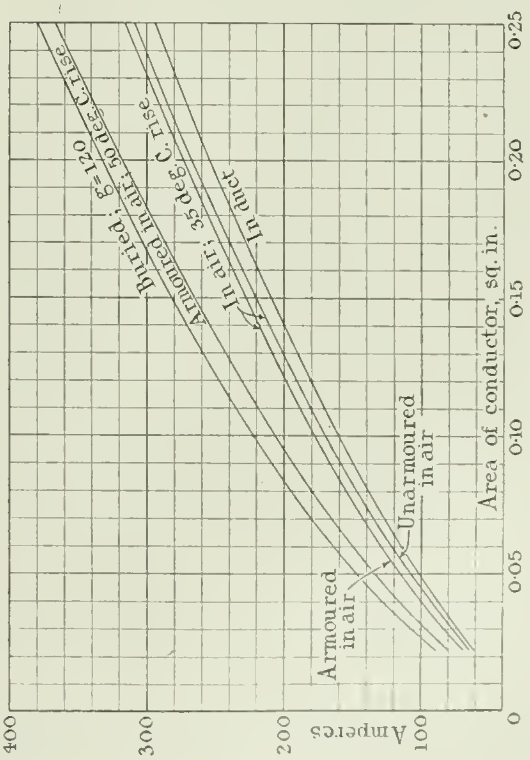


FIG. 52.—2 200-volt 3-core cables under different conditions of laying (not earthed).

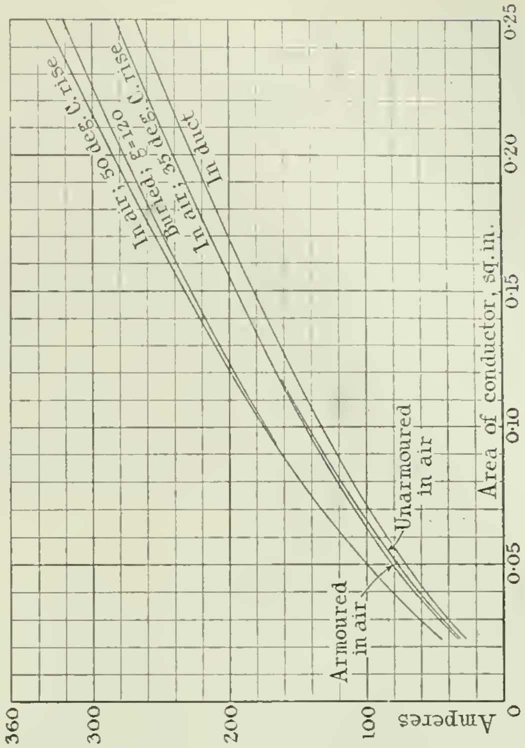


FIG. 53.—11 000-volt 3-core cables under different conditions of laying (not earthed).

## BIBLIOGRAPHY.

Forchheimer : "Isothermals around Buried Water Pipes," *Zeitschrift der Architekten und der Ingenieure Verein*, 1888, vol. 34, p. 175.

Kennelly, A. E. : "Carrying Capacity of Electric Cables, Submerged, Buried or Suspended in Air," *Electrical World*, 1893, vol. 22, p. 183.

Chermak : "Heating of Conductors," *Sitzungsberdler Wiener Akad, der Wissensch*, 1894.

Diessellhorst, H. : "Electrically Heated Conductors," *Annalen der Physik*, 1900, vol. 1, p. 312.

Wilkens, K. : "Heating of Underground Cables," *E.T.Z.*, 1900, vol. 21, p. 413 ; *Science Abstracts*, 1900, No. 1924.

Apt, R. : "Heating of Underground Cables," *E.T.Z.*, 1900, vol. 21, p. 613 ; *Science Abstracts*, 1900, No. 1925.

Herzog, J., and Feldmann, C. : "Heating of Electric Cables," *E.T.Z.*, 1900, vol. 21, p. 783 ; *Science Abstracts*, 1901, No. 225.

Weiler, W. : "Heating of Electric Conductors," *Elektrotechnische Rundschau*, 1901, vol. 19, p. 42 ; *Science Abstracts*, 1902, No. 211.

Humann, P. : "Heating of Cables," *E.T.Z.*, 1903, vol. 24, p. 599.

Teichmüller, J. : "Heating of Underground Cables," *ibid.*, 1904, vol. 25, p. 933.

Kath, H. : "Loading of Cables," *ibid.*, p. 969.

Apt, R., and Mauritius, C. : "Heating of Underground Three-phase Cables," *ibid.*, p. 1008. Letter to Editor, *ibid.*, 1905, vol. 26, p. 207.

Humann, P. : "Heating of Three-core Cables," *ibid.*, p. 533.

Mie, G. : "Heat Conduction in a Twisted Cable," *ibid.*, p. 137.

Teichmüller, J. : "Heating of Electric Mains." [Stuttgart, 1905.]

Fisher, H. W. : "Data relating to Electric Conductors and Cables," *Transactions of the American Institute of Electrical Engineers*, 1905, vol. 24, p. 397.

Picou, R. V. : "Capacity and Heating of Underground Cables," *L'Industrie Electrique*, 1906, vol. 15, pp. 245, 281 and 445.

Teichmüller, J., and Humann, P. : "Heating of Cables," *E.T.Z.*, 1906, vol. 27, p. 579. Article on : "Experiments on the Heating of Underground Cables," *ibid.*, p. 813.

Kennelly, A. E., and Shepard, E. R. : "The Heating of Copper Wires by Electric Currents," *Transactions of the American Institute of Electrical Engineers*, 1907, vol. 26, p. 969.

Gacogne, M. : "Temperature of Electric Conductors," *La Lumière Electrique*, 1908, vol. 1, p. 363.

Roy, L. : "Heating of Conductors by Electric Current," *ibid.*, pp. 99, 134 and 163.

Junkersfeld, P., and Schweitzer, E. O. : "High-Potential Underground Transmission," *Transactions of the American Institute of Electrical Engineers*, 1908, vol. 27, p. 1499.

Lichtenstein, L. : "Experimental Determination of the Heating of Cables," *E.T.Z.*, 1909, vol. 30, p. 389.

Roy, L. : "Influence of Ventilation upon Working Temperatures of Bare and Insulated Conductors," *Bulletin de la Société Internationale des Electriciens*, vol. 10, p. 69.

Mangus, G. : "Note on Tests made by the Central Laboratory of Paris," *ibid.*, p. 597.

David, C. : "Tests of Electric Cables (Battleship Installation)," *ibid.*, p. 511.

Melsom, S. W., and Booth, H. C. : "The Heating of Cables with Current," *Journal I.E.E.*, 1911, vol. 47, p. 711.

Wagner, J. : "Considerations Concerning the Permissible Load on Cables in Germany and England," *E.T.Z.*, 1912, vol. 33, p. 501.

Mosman, C. T. : "Notes on Underground Conduits and Cables," *Transactions of the American Institute of Electrical Engineers*, 1912, vol. 31, p. 755.

Atkinson, R. W., and Fisher, H. W. : "Current Rating of Electric Cables," *ibid.*, 1913, vol. 32, p. 325.

Dushman, S. : "Heating of Cables carrying Current," *ibid.*, p. 333.

Melsom, S. W., and Booth, H. C. : "Heating of Buried Cables," *Journal I.E.E.*, 1914, vol. 52, p. 779 ; also 1915, vol. 53, p. 328.

Beaver, C. J. : "Cables," *Journal I.E.E.*, 1915, vol. 53, p. 57.

Imlay, L. E. : "Effect of Moisture in the Earth on Temperature of Underground Cables," *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, p. 233.

Powell, R. C. : "Temperature Rise of Insulated Lead-Covered Cables," *ibid.*, 1916, vol. 35, p. 1017.

Matsumato, H. : "Carrying Capacity of Underground Cables," Electrotechnical Laboratory (Tokyo), Report No. 24 (1916).

Cozzens, H. A. : "Heating of Underground Cables," *Electrical World*, 1916, vol. 68, p. 953.

Picou, R. V. : "Limiting Values of Current in Armoured Underground Cables to be Located in Trenches," *Révue Générale de l'Électricité*, 1917, vol. 1, p. 410. "Current-carrying Capacity of Cables," *National Electric Light Association Bulletin*, 1917.

Harper, J. L. : "Problems of Operation and Maintenance of Underground Cables," *Transactions of the American Institute of Electrical Engineers*, 1917.

Bang, A. F., and Louis, H. C. : "The Influence of Dielectric Losses on the Rating of High-Tension Underground Cables," *ibid.*, p. 431.

Newton, G. J. : "Underground Construction," *ibid.*, 1918, vol. 37, p. 203.

Schweitzer, E. O. : "Increasing Carrying Capacity of Underground Cable," *Electrical World*, 1918, vol. 71, p. 613.

Soleri, E. : "Current Intensities in High-Voltage Cables," *Elettrotecnica*, 1918, vol. 5, pp. 54 and 75.

Article on : "Accomplishing Reduction of Duct Temperatures," *Electrical World*, 1918, vol. 71, p. 823.

Article on: "Ventilation of Ducts Reduces Underground Cable Failures," *Electrical Review* (*Chicago*), 1919, vol. 74, p. 561.

Freret, R. L.: "Heating of Underground Cables," *Journal of the Engineers' Club of Philadelphia*, 1919, vol. 36, p. 301.

Charlton: "Current-Carrying Capacity of Electric Cables," *Journal of the American Society of Naval Engineers*, 1919, vol. 31, p. 764.

Clark, W. S., and Shanklin, G. B.: "High-Tension Single-Conductor Cable for Polyphase Systems," *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 663.

Wilder, W. S.: "Thermal Conductivity of Underground Ducts," *Electrical World*, 1920, vol. 75, p. 14.

Atkinson, R. W.: "Current-Carrying Capacity of Lead-Covered Cables," *Journal of the American Institute of Electrical Engineers*, 1920, vol. 39, p. 831.

Torchio, P., Clark, W. S., Del Mar, W. A., Fisher, H. W., Atkinson, R. W., and Roper, D. W.: "Effect of Heat on Cable Paper Insulation," *ibid.*, 1921, vol. 40, pp. 113, 120, 131, 183 and 201.

Kapp, R. O.: "Economic Aspects of Extra-High-Tension Distribution by Underground Cable," *Journal I.E.E.*, 1921, vol. 59, p. 94.

Report on "Research on the Heating of Buried Cables," *ibid.*, p. 181.

De Muth, W. B.: "Industrial Underground Cables," *Power Plant Engineer*, 1921, vol. 25, p. 758.

Höchstädter, M.: "The Ionization Point of H.P. Cables," *E.T.Z.*, 1922, vol. 43, pp. 575, 612 and 641.

Enke, F.: "Heating of Cables." [Stuttgart.]

Feldmann, C.: "On the Heating of Stranded Multiple Cables with Metallized Cores," *E.T.Z.*, 1922, vol. 43, p. 1500.

Melsom, S. W., and Booth, H. C.: "Rating of Cables for Intermittent or Fluctuating Loads," *Journal I.E.E.*, 1923, vol. 61, p. 363.

## Discussion before The Institution, 1 March, 1923.

**Mr. Ll. B. Atkinson**: The results of the research are presented to the Institution by the two authors, Mr. Melsom and Mr. Fawssett, in the form of a report to the Electrical Research Association, but as a matter of fact the great bulk of the experimental work has been done by these two members. In some ways I have been so closely connected with the growth of this report that perhaps it would not be reasonable and proper for me to make any criticisms now. I am therefore going to take this opportunity to say a few words on what appears to me to be a very urgent moral arising from this report. The great discoveries in electrical science, as in all other sciences, have in the main been made by single individuals. That will in all probability continue to be the case; that is to say, great minds concentrating their genius on some problem and reaching sometimes by logical processes, sometimes by intuition, and sometimes, we may almost be tempted to believe, by a transference of thought from outside, conclusions which they experimentally verify and which at one stroke seem to open up new worlds. That method of research by individuals will, I am quite sure, continue. But we must remember that it was an electrical man—Edison—who invented or discovered the process of a mass attack on problems by organized forces. I believe that the Menlo Park laboratory was the first instance in the history of the world of the realization of the definite belief that by putting a sufficient number of well-trained people on to almost any problem it could be solved, and that within a reasonable time. Earlier in the present week there took place the official opening of the General Electric Company's new research laboratories, an institution which already possesses a fine preliminary staff under the directorship of Mr. C. C. Paterson. That institution is an example of another form of research; that is to say, where a large concern deliberately establishes a department to solve its own problems and to make discoveries which it may use for its own benefit and its own profit, always realizing that necessarily, in the long run, the discoveries must profit others. In a smaller way, with less means and therefore at present more circumscribed as to its outlay, we have the Electrical Research Association, in the foundation of which this Institution was associated, where again the problem of research was approached from a different direction. Some researches there are which appeal and are of use to much wider groups of people than a single firm—which may, in fact, be of use to everybody in the electrical industry. It is the function of such a Research Association to undertake, at least as part of its work, the solution of problems which are of the widest application to every branch of the industry. A research such as the one with which we are now dealing is of no use unless it is published widely, and unless everybody in the electrical industry can and will make use of it. So far, however, although that is the case with this particular research, as it will be with others that the Electrical Research Association will develop, the burden of these researches is falling on a very few shoulders, and in some cases on the shoulders of those who are perhaps least interested in the matter. For instance, if, as I shall hope to show presently, the present report will result in some cases in less cable being required for a given service, it certainly appears somewhat curious that, apart from the contribution from the Department of Industrial Research, such a research should be paid for by the manufacturers of cables and not by the users. The manufacturers are, however, well aware that anything that can be done to cheapen the capital outlay on electric work is to their benefit in the long run, as well as to the benefit of everybody else. There is at times a feeling in some quarters that the Electrical Research Association has not so far produced any great results, or even results worthy of the expenditure and trouble taken. I think I shall be able to show that

that is a short-sighted view. The Association has, in fact, only existed for $2\frac{1}{2}$ years, and the present report is one of its first fruits. This report, within the limits to which it goes—that is the 11 000-volt cable—and including all the ordinary cables, puts us to-day for the first time in this position, that engineers or supply companies who have decided what cable will be used, and how deep it will be buried and, by a simple experiment, have determined how much moisture there is in the soil, and how many other cables are laid near it (all simple, easily-determined physical facts) are in the position, by the aid of this report, to say definitely what is a reasonable and proper loading (for a given temperature-rise) to put upon such a cable. Even if it be true that some cables are shown to be already overloaded, that is almost as great an advantage to the user as to find they are underloaded, because he is diminishing his future risk. At a conservative estimate, not less than £40 000 000 worth of underground cables are in use in this country alone for the purpose of distributing electricity. I think, also, it is no exaggeration to say that, with these tables before them, almost any supply undertaking may definitely improve the use of its cables by 10 per cent, either by diminishing the risk or increasing the loading, with perfectly definite knowledge. If that be a fair estimate, then the value in money of this report to the industry is something of the order of £3 000 000 to £4 000 000. If that be a correct way of looking at it, and if we say that cables are now being put down in this country at the rate of something like £2 000 000 to £3 000 000 worth a year, then, with the superior use of cables to be obtained as a result of this report, £200 000 to £300 000 a year will be gained by the industry. A certain group of manufacturers, belonging to two large Associations, has so far found all the sinews of war, except for a certain amount of very valuable help given now and in the earlier stages by this Institution. Now, however, we must press others to give financial assistance. The supply industry has not so far, perhaps, had an opportunity of doing so, but steps are being taken to remedy this and to enable them to join the Research Association as members. In saying this I must call attention to the great help given by the company with which Mr. Fawssett is connected, both in material support and in allowing its officials to devote much time to the work.

**Dr. A. Russell:** The authors discuss the heating of a three-core cable when only two of the cores are carrying current. On page 546 they show that the ratio of the thermal resistance between the three cores and the sheath to the thermal resistance between the two cores and the sheath is as 91 to 100, but the ratio of the electrostatic capacity between two cores and the sheath to the capacity between three cores and the sheath is approximately as 81 to 100. If the insulating material acts as a homogeneous medium to heat-flow, the two ratios ought to be the same. There must be a reason for the difference. When only two cores are loaded the sheath gets rid of less heat than when three cores are loaded. The sheath therefore is at a lower temperature and so also the insulating material is at a lower temperature. Hence, if the thermal resistivity increases as the temperature increases, this would explain the discrepancy. If the thermal resistivity has a temperature coefficient—just as the insulation resistance has a temperature coefficient—then the rating of cables for use in hot countries would be different from the rating in cool countries. The authors discuss the heating of conductors in air and call the amount of heat emitted per sq. cm of the surface of the cable per degree C. and per second the "emissivity constant." It is well known that this "constant" is greater for cables of small diameter than for large cables. It can be shown that it varies inversely as the square root of the diameter of the cable. An interesting experiment is described at the end of the report, where an experimental three-core cable is constructed and certain measurements are made to find out the error in the Russell formula when used at a part of the scale where it does not apply. The effect on the capacity of giving the cores a twist round the axis of the cable is measured. It is found that this twist—"lay," I think, is the proper term—has little effect on the capacity and therefore also on the thermal resistance. The reason of this is possibly that the twist increases the effective length and therefore the resistance of the core per unit length. There is consequently more heat to get rid off. At the same time also, whilst there is more metal per unit length there must be less heat-resisting material. These produce opposite effects and hence may produce a very small resultant effect. It is interesting to remember that the theory of the radial conduction of heat in cylinders which the authors have applied to everyday practical work was first given by Fourier in his *Théorie Analytique de la Chaleur* published over 100 years ago.

**Mr. H. Brazil:** I entirely agree with Mr. Atkinson's remarks on the very valuable work done by the Electrical Research Association, and think that the whole profession is deeply indebted to them. I cannot, however, agree with him that any engineer with this report before him will find it quite simple to determine, under any circumstances, what size of cable he requires to deal with a given load, and to what figure he must reduce the current on existing cables in order to be safe. On page 542 is given a table showing the permissible temperature-rise, and the figures vary from 25 deg. C. (German) to 50 deg. C. (British) and 85 deg. C. (Japanese), and I believe that the American figure approximates to the Japanese. Presumably cables are working at or near this highest figure, and it is therefore difficult to come to a decision as to which figure to use. Again, if cables are working at 85 deg. C. rise, it is very unlikely that an engineer working his cables at, say, 60 deg. rise would reduce the figure to 50 deg. in consequence of this report. Another difficulty that arises is the variation in the thermal resistivity of the soil through which the trunk main has to pass in getting from generating station to substation. In most cases the main will start in the country, and then penetrate through the outskirts right into the town or city. Those who have to lay mains in large towns will appreciate that all kinds of made-up soil have to be dealt with. In some cases there is scarcely any soil left, and the main has to be laid amongst pipes and ducts of various kinds. What value for the thermal resistivity should, in the authors' opinion, be used in this case? If the main is of the same size throughout its whole length, this size must be governed by the thermal resistivity of the worst soil through which it has to pass or, alternatively, the size of the cable must be varied as the thermal resistivity of the soil varies, which is, I am afraid, an impossible proposition.

**Professor E. W. Marchant:** The great value of the report lies in the fact that it gives due weight to the very many variables that have to be considered, such as the character of the soil and the grouping of the cables, and it deals, of course, with high-pressure three-core cables. In common with Mr. Atkinson, I feel that the report will result in the saving of a great deal of money to supply undertakings. I propose to discuss one or two points in connection with the work that has been done. First of all, there is a difference shown for the permissible temperature-rise when a cable is laid direct in the ground and when it is laid in ducts; in one case it is 50 degrees C. and in the other 35 degrees C. The only reason given for this difference is the fact that there is greater liability to abrasion when the cable is laid in ducts. As stated in the report, the difference in permissible temperature-rise gives a difference of over 12 per cent in the carrying capacity of the cables, and tells very heavily, therefore, against the use of cable laid in ducts. Have the authors any definite information as to the abrasion of the lead sheathing of cables when they are laid in ducts? On page 537 it is stated that where current is passed through a cable there is an increase in the moisture surrounding the cable. It seems to me that this must be more or less accidental; I cannot imagine how the passage of current through a cable can tend to increase the moisture surrounding it. There is a reference in the report to the fact that the cable trough sometimes acts as a drain, and I think that is what must have happened in this instance. On page 543 it is stated, and I think quite rightly, that a cable route can sometimes be traced out by the drying of the ground above it. I should like to suggest the stream-line method used by Dr. Hele-Shaw which was shown before this Institution some years ago, for plotting out the stream-lines of heat-flow in a three-core cable. It was used in the first instance for tracing out lines of force, and was used here to show the lines of force from the armature tooth to the field magnet. It is stated in the report that the relative expansion of the core and the sheath is comparatively small. In one of the cases quoted, the actual increase in length of the conductor is about 1 inch, and the increase in length of the sheath is about $\frac{3}{4}$ inch. That means, of course, only $\frac{1}{4}$ inch relative motion of the core and the sheath, and the risk of trouble is therefore not great. I think the fact that the core tends to expand more than the sheath is important, and might not be expected, since the coefficient of expansion of lead is greater than that of copper. That, I think, has an important bearing on the use of aluminium cables. The coefficient of expansion of aluminium is about 50 per cent greater than that of copper, and therefore the liability to trouble from expansion is likely to be much more when aluminium is used than when copper is employed. It is stated in the report that the dielectric loss in cables is negligible at a pressure of 11 000 volts, and I think it is stated that the dielectric loss will increase rapidly when the temperature rises above a certain definite figure. Is not the dielectric loss due to temperature-rise caused by direct conductivity rather than by dielectric loss, as the term is ordinarily understood? The specific resistivity of a dielectric falls very rapidly indeed as the temperature rises, whereas I do not think that dielectric loss due to dielectric hysteresis alters to any appreciable extent with increase in temperature. I should be glad if the authors would give some definite information on that point. It would also be instructive to have some figures for the sheath losses in single-core cables carrying single-phase current. Suggestions for the use of such cables have been put forward within the past few months, and a good many figures of sheath losses have been published, but the information is not very complete.

**Mr. T. N. Riley:** The authors state on page 545 that the balanced-load condition is the least favourable from the point of view of temperature-rise. It is common practice to use cables for three-wire working in which the neutral wire is half the section of the two main cores. In this case it is not correct to state that the balanced-load condition is the least favourable. Let $I$ and $(I - i)$ be the currents in the main cores ($i$ being the current in the neutral core); $R$ = resistance of each main core; $2R$ = resistance of neutral core. Then the heat developed is proportional to: $I^2R + (I - i)^2R + i^2(2R) = 2I^2R - iR(2I - 3i)$. In the balanced condition when $i = 0$ and again when $i = \frac{2}{3}I$ the heat developed is the same, and between these points the heat developed is reduced. If $i$ exceeds $\frac{2}{3}I$ the heat developed increases and becomes a maximum when the current in one core is zero, when the heat developed is 50 per cent greater than in the balanced-load condition. It is unlikely in ordinary circumstances that the unbalanced load will ever be such as to make $i$ greater than $\frac{2}{3}I$, and the case which the authors have taken will meet ordinary practice even if the third core is of half section. It is then difficult to see how a neutral core of equal section to the other two, as assumed by the authors, can be justified. Mr. Melsom stated in the discussion that the authors had not found any satisfactory method of plotting the lines of heat-flow. It appears to me that a similar method might be used to that described by Emanueli * in a paper dealing with the determination of the electrostatic field in a three-phase cable. It would at first sight seem quite possible to determine the lines of heat-flow for any cable under any system of loading. The cable would be represented by tubular conductors surrounded by a tubular lead sheath immersed in an electrolyte, and each conductor would be charged to a potential above the sheath proportional to the heat developed in it under the assumed load conditions. Emanueli used water as his electrolyte. The use of alternating current avoids polarization effects, and an electrodynamometer is used to give a "null method" detector and avoid disturbance of the field. The connections for exploring the thermal field are shown approximately in Fig. A. Emanueli's experimental arrangements are fully described in the paper referred to. One advantage of this method is that it would enable sector-shaped cores to be dealt with in a manner impracticable by calculation, and it would afford a valuable check on Mr. Wedmore's graphical method in Appendix 4, which does not appear at all easy to apply with accuracy to sector-shaped conductors. The method would not, of course, allow for any difference in heat conductivity of the worming and the main core insulation due to difference of material or tightness of packing. It would be interesting to know whether the authors found this to be appreciable. I use "worming" here in the sense of the material employed to fill the interspaces between cores. There is an alternative method which seems to me to be feasible. If in any cable the dimensions were magnified to any extent, keeping the proportions the same, the thermal field would be similar. A model could therefore be constructed sufficiently large to use the thermo-couple method already employed for investigating the heat-flow in the ground outside the cable (see page 543 of the report). The actual material used as filling would only affect the magnitude of the thermal resistance and not the lines of heat-flow. The effect of the worming might then be studied by using two materials of different thermal resistivity for the portions of the dielectric representing core or belt insulation and worming. If the thermal field is determined, a correction for filling material and absolute dimensions could then be very simply applied. The authors showed figures giving a comparison of the current loading of British and German cables. If we take the 11 000-volt case, the German standard thickness of dielectric is only 0·24 in. as against 0·3 in. in the British case, and for cables laid direct in the ground that would give a better cooling effect to the German cables and enable them to run at a higher current loading. In the opinion of the authors, is the difference in insulation thickness sufficient to account for the increased rating of the German cables?

---

* *L'Elettrotecnica*, 1921, vol. 8, p. 573.

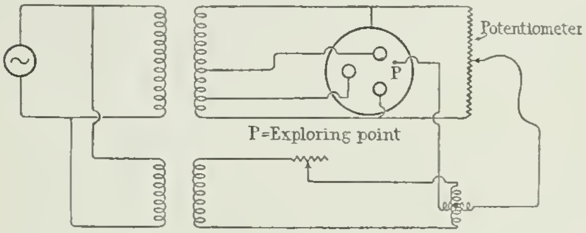


FIG. A.

**Mr. P. Dunsheath**: When the Preliminary Report appeared two years ago, some of us were disappointed because the contents were not such as could be applied to everyday problems of current rating, and we suggested that a simpler treatment based more closely on the thermal Ohm's law would be helpful. I am glad to find that, either because of the suggestions then made or for some other reason, the thermal-resistance treatment has been entirely adopted, with eminently satisfactory results. On page 535 two values have been adopted for thermal resistivity, one of 750 and the other of 550, the former for pressures up to and including 2 200 volts and the latter for pressures between 2 200 and 11 000 volts. Reasons are given for this classification, but they are not very convincing. On the same page the following statement occurs: "In view of the cost of manufacture it was considered unreasonable to expect that the lower-pressure cables would normally have a value of thermal resistivity as low as that of the higher-pressure cables." I should be glad if the authors could give a little more information on this point. I submit that, taking the whole of this and the previous report, the evidence is insufficient to warrant the adoption of those two values and that particular classification. Considering manufacturing operations, we should expect the values to be in the opposite direction. I think that the point should be verified very carefully before this is put forward as the last word. The footnote on the same page states: "Higher values have been adopted for cables with conductors having a sectional area less than 0·06 sq. in. to allow for the difficulties in manufacturing small cables." What is the reason for that statement? On page 538 the question of the thermal resistance of the soil is referred to. On later pages, and in particular page 544, the problem is worked out in detail. This, of course, is one of the difficulties of the whole investigation into the rating of buried cables. The method adopted in the report seems to be to make the assumption that the isothermal line coincides with the surface of the ground, and then to modify it by an arbitrary constant in order to make that assumption agree with the figures obtained, knowing at the same time that the assumption must be wrong. It is stated later in the report that the surface of the ground on a damp day dries over the cable, but not to any extent on either side. It does not seem right to assume that Kennelly's formula is correct and then add an arbitrary constant to make it fit the results. The real reason for the discrepancy seems to be that there is a temperature gradient in the ground before the cable carries any current at all, as is shown by some of these curves. In the summer, the surface of the ground is considerably hotter than the ground at a depth of two or three feet, and in the winter the gradient is reversed. Formula (26) shows that the deeper the cable is buried the greater will be the thermal resistance of the soil, and consequently the greater will be the temperature-rise. As a matter of fact, a cable buried deeper in the summer is put into a cooler spot, and therefore the reverse may hold; that is to say, the greater the depth the lower may be the temperature-rise. On page 541 another fundamental on which the whole of Table 31 hinges is that of the maximum temperature adopted. The figures are given as 65° C. for cables laid direct, and 50° C. for those in ducts. I think that the reasons for adopting the first-named figure are very good indeed. A previous speaker said that the Japanese were adopting higher maximum temperatures. The Americans also are doing so, but a report published three months ago in America showed the number of faults they allowed per mile of cable. The figure was ridiculously high from a British standpoint, so the fact that other nations are adopting higher temperatures is no justification for our adopting higher figures than those mentioned in the present report. The arguments put forward for the maximum temperature of 65° C. are very strong indeed, but I am not so sure about those advanced to support the figure of 50° C. for cables in ducts. In American practice, where ducts are more common, the temperatures are very much higher than that, and I hardly think that the abrasion trouble referred to is a sufficient reason for having two maximum temperatures for the same dielectric. The paragraph on page 541 commencing: "The actual difference in permissible current-loading . . .," should, I think, read: "The actual difference in permissible current-loading between rises of 50 degrees C. and 35 degrees C., corresponding to final temperatures of 65° C. and 50° C. respectively . . ." In formula (49) * $L$ should be in the denominator and not in the numerator, because the thermal resistance goes down with the length. On page 553 the time to attain the maximum temperature is dealt with. Not many people seem to realize that if a cable is buried in the centre of an infinite medium and quite a small current is passed through it, the temperature will rise indefinitely. This would not, of course, occur in practice, but I think that that phenomenon throws much light on the practical problem. I think that the sub-title "Effect of 'worming' on the capacity of the electrostatic model" on page 567 is incorrect. What is intended here is "lay," not "worming," and I suggest that the correct technical term be adopted.† In conclusion, I should like to emphasize an important feature of the report. For a long time a need has been felt for a set of current-carrying tables which could be accepted as standards, but it was important that they should be published in such a way as to command confidence. The authors must have been tempted at times to dwell on more academic points, but they have gone, I think wisely, straight to the practical problem, and so have produced a precise authoritative statement which will command the respect of engineers which it deserves.

**Mr. E. B. Wedmore**: Mr. Atkinson has already dealt admirably with this report from the point of view of the Electrical Research Association, but I should like to add a few remarks. Members are aware that the Association has in hand other researches which affect the whole industry. I suppose it is true to say that the whole of the work of the Association is and will be of value to the whole of the industry. We have researches now in hand, however, which are of particular value to those engaged in power supply. We are conducting researches which will add to the economical use of overhead line material, researches on the construction of poles, which will undoubtedly lead to a change in the design of poles designed for carrying overhead lines, and researches on switchgear, amongst others in this category. Mr. Atkinson has referred to £200 000 to £300 000 a year as the saving likely to accrue to the industry as a result of this report alone. I feel that the Association can reasonably seek to secure at least 10 per cent of this sum. There is a particular claim which I should like to put forward at this stage to those members who are connected with electric supply. Manufacturers are not yet free of the financial difficulties through which the whole industry has been passing of recent years. Business is turning the corner, but only slowly. On the other hand, I think it is a fact that power supply companies have well turned the corner. Undoubtedly the municipal supply authorities also, who will benefit by these tables, are in a happier position financially than they were a few years ago. This is a favourable time, therefore, for supply undertakings to consider their indebtedness to the Association and to consider the possibility of co-operating in the work now being done, work from which they will so obviously derive benefit. It has been briefly indicated that the Association has in preparation a scheme of Associate Membership for bringing these people more closely in touch with us. We desire their co-operation in every way. The whole effort of the Association is co-operative, not only in its financial aspects, but in every direction; we want the whole-hearted co-operation of everyone who is interested in research as a means of advancing the industry. It is hoped to distribute particulars of this scheme of Associate Membership to all those interested, and we hope that power companies, municipal authorities and large users will see their way to appoint representatives to co-operate with the Association in the capacity of Associate Members, and help to finance our researches by substantial subscriptions. We have already had promises recently of £250 to £500 from each of several large corporations engaged in power supply, towards particular researches.

**Mr. P. V. Hunter**: I should like specially to draw the attention of engineers to those tables in the report which show the permissible loading which may be adopted in the case of cables laid together. In the past there has been a fairly general knowledge on the question of the actual heating of the ordinary types of cables when laid according to the methods in general use, but there has been no reliable information available as to the effect of the mutual heating of cables in the same trench. The information given in Table 37 of the constant to be applied when cables are laid at different spacings in the same trench is therefore, I think, of very great value indeed, and is hardly given sufficient prominence in the report. Have the authors any information for rather larger separations than the 12 in. given? In many cases it is customary to space the cables rather farther apart, up to 18 in. or even 2 ft. There is also the question of the cause of temperature-rise in cables laid direct in the ground. Various mathematicians have visualized it in different ways, and I gather that the authors could find no test-results which agree with the mathematical formulæ. It seems to me that the assumption that all the lines of heat-flow eventually reach the surface of the ground must be right. In practice the energy must be dissipated in the atmosphere. The weakness in that particular mathematical formula seems to lie in the assumption that the surface of the ground is also an isotherm. If a cable were buried at such a depth that the lengths of the lines of heat-flow from the cable to the surface were all approximately equal, the surface of the ground would approximate to an isotherm. For this condition to hold, however, the depth must be very great as compared with the diameter of the cable: probably many times greater than is the case in ordinary practice. For this reason it is necessary to make a rather large correction to the formula—as much as 33⅓ per cent, I understand.

---

* Corrected for the *Journal*.

† This suggestion has been carried out.

(*Communicated*): There is one other matter which appears to require some further consideration, namely the permissible current loading of cables in air. On page 522 it is stated that for cables in air and drawn into ducts the temperature-rise allowed is 35 deg. C., the maximum permissible temperature being 50° C., from which it is deduced that the atmospheric temperature is 15° C. In the case of railway companies it is common practice to suspend high-tension cables in air and exposed to direct sunlight, and it seems to me that at certain times of the year the atmospheric temperature must substantially exceed 15° C. I should expect it at times to reach 40° C. Assuming for the moment the same temperature-rise, namely 35 deg. C., this would give a total temperature of 75° C., which seems likely to be the condition which would result if cables suspended in this way were loaded in accordance with Tables 16 to 21. It is probable that for these particular conditions the limit of maximum temperature of 50° C. need not be adhered to, as this is primarily a limit set in connection with cables drawn into ducts. For cables laid underground the limit is 65° C., which is still 10 deg. less than the 75° C. mentioned above. A particular cable carries its maximum load only occasionally, i.e. when circumstance requires some of the cables to be out of service at the time of maximum load. For a temperature of 75° C. to be reached these cables have to be out of service not only at the time of maximum load but also during that brief period of the year when the atmospheric temperature is highest. For this reason, therefore, the probability of any particular cable attaining to the temperature of 75° C. is small, and it is doubtful if any harm would accrue from such a temperature if it occurred for only a few hours in the course of several years, provided the cables are for working pressures not exceeding 11 000 volts, where the increment of dielectric loss with temperature is not a material factor. On the whole, therefore, the conditions are probably not so alarming in practice as they would appear to be on paper, but in view of the imminence of schemes of railway electrification and of the tendency for the advisers of railway companies to adopt this mode of erection for cables, it would probably be of value to the industry if the Committee would give it some more special consideration than has been done in the report. The capital expenditure involved is several millions of pounds eventually, and the railway companies might therefore be asked to contribute a little money for a special series of tests, the results of which could be embodied in a small supplementary report.

**Mr. P. Rosling**: I think that the wrong terminology* is used in regard to the concentric cables, where columns are headed "Centre Point Not Earthed" and "Centre Point Earthed." Concentric cables may be used for single-phase transmission, and I think that the headings should be "Outer Conductor Not Earthed" and "Outer Conductor Earthed." I take it that the loadings given are safe loadings for these cables in certain circumstances; it does not by any means follow that they are the loadings which it will pay best to put on the cables. They may be satisfactory for temporary running, but an examination of the losses entailed by these loadings will show that to-day, with the high price of coal and low price of copper, such loadings will not be economical in usual practice.

**Mr. E. T. Williams**: There is one small point which has not been referred to in the report, namely the emergency loading of cables for a short time. All power engineers know that when laying down networks it is desirable to look to the emergency and to consider how the supply can be kept going in the event of one cable breaking down, and to what extent cables can be over-run without permanent injury, or even any injury at all. Information on that aspect of the work would be of very great value to engineers engaged in designing lay-outs. In common with Mr. Atkinson and Mr. Wedmore, I feel very strongly that not only financial support but sympathetic support should be given to those who are trying to advance this cause of research. In my official position I have come very intimately into contact with not only the value of this research in experimental work but also the great difficulties that have to be contended with.

**Mr. W. A. Del Mar** (*communicated*): The source of this report, the names of the authors and of the Committee members, lend great authority to its recommendations and ensure its usefulness to British cable users. It may be of interest, however, to consider how this report would be received if presented to an American audience. In this case the emphasis would have to be put on the use of cables in ducts, this being the almost universal practice in America. The Standards of the American Institute of Electrical Engineers allow the insulation at the surface of the conductor to attain a temperature of 85° C. less 1 degree C. per kilovolt working tension in the circuit. Thus a cable for 11 000 volts may be operated at a temperature of $85 - 11 = 74°$ C. This formula is an empirical one approximating a rational one based upon the assumption that cables must not be allowed to carry a greater load than a certain percentage of that load which would give cumulative heating with insulation of the power factors obtaining when the rule was formulated. Practical operating experience was also drawn upon in arriving at the final formula. This rule had served for about 8 years when the general reduction of dielectric losses and the rise in commercial tensions led to its re-appraisal by a committee of the Institute. It was pointed out that while the rule gave satisfactory results up to about 25 000 volts, it gave temperatures which were obviously too low for the new 33 000- and 44 000-volt cables. The manufacturers of these cables were willing to guarantee them for continuous operation at 60° C., whereas the rule gave 52° C. and 41° C. for 33 000- and 44 000-volt cables respectively. The Institute, however, was not in possession of sufficient experi-

* Corrected for the *Journal*.

mental data to make an adequate revision of the rule and it was therefore decided to hold a meeting devoted to a symposium on the failure of insulation under stress, and to make this the starting point of an exhaustive research. The symposium was held at Niagara Falls, Ontario, in June 1922 and the research work was started at about the same time, under the direction of Professor Bush, of the Massachusetts Institute of Technology. This work is financed by the National Electric Light Association, which is an organization of central station companies, and is under the control of a joint committee of that Association and the American Institute of Electrical Engineers. In 1921 the basic figure of the American rule, 85° C., was discussed in a symposium on the heating of low-voltage cables. This symposium is quoted in the report under discussion, and it is incorrectly stated that the temperature-limits for impregnated paper cables proposed by American engineers in 1921 were " all based on consideration of the mechanical properties of the paper only." As one of the authors and as chairman of the committee under whose auspices the papers were presented, I can say with authority that the authors took into consideration all operating features of which they knew affecting low-tension cables, i.e. cables in which neither dielectric stresses nor dielectric losses have any perceptible influence. In particular, the subject of thermal expansion was fully considered. It seems to me that the authors of the report beg the question at issue when they say that " after full consideration of all the various factors involved, it was decided to adopt 65° C. . . . for the maximum temperature of the conductor for armoured cables up to and including 11 000 volts working pressure laid direct in the ground," and " in view of the fact that a cable drawn into a duct is free to move lengthways along the duct and cause injury to the lead by abrasion, it was considered that the permissible temperature should be lower than that for cables laid direct in the ground. It was decided, therefore, to adopt 50° C. for the maximum temperature of the conductor, etc." When hundreds of miles of cable are operating successfully at temperatures from 24 to 35 degrees C. higher than the 50° C. adopted, the exact reasons for adopting the latter figure should be stated. The statement that it was adopted after " full consideration of all the factors involved " is rather like the embarrassing moment at a mathematics lecture when the professor says " it is obvious that " and then the whole thread of the discourse is lost. It would seem that the major part of the research should have been directed toward ascertaining and giving full reasons for the temperatures adopted. This is the course which, as explained above, has been adopted by the Cable Research Committee of the National Electric Light Association and American Institute of Electrical Engineers. The importance of the maximum allowable temperature may be seen at a glance if the ambient temperature of a duct line be assumed to be 30° C., as the permissible rise for an 11 000-volt cable would be 44 degrees in American practice and 20 degrees in British practice. An assumption of 15° C. duct-line ambient temperature is difficult to understand, especially in view of the reduction factors to be used in calculating the carrying capacity when several cables are present. The relative carrying capacities of a cable under the American and British rules would then be in the ratio of $\sqrt{(44)} : \sqrt{(20)} = 1\frac{1}{2}$ approximately. It is hard for an American to understand why British cables should be loaded to only two-thirds of the current that American cables normally carry. There also seems to be a confusion of thought where Kelvin's law is cited as a limiting factor. This law does not give 50° C. as the economical temperature regardless of the cost of labour, coal and copper. The maximum permissible temperature should not be confused with the most economical temperature from the point of view of copper losses. The work on Mie's formula is very thorough and useful and will be greatly appreciated by American cable engineers.

**Mr. A. Rosen** (*communicated*) : Dr. Russell has suggested that the thermal resistivity of the dielectric might vary with the temperature. This possibility occurred to me some little time ago, and the following experiment was carried out to investigate the matter : A 220-yard length of three-core 0·15 sq. in. 22 000-volt cable, coiled on a wooden drum, was immersed in a comparatively large volume of water, and sufficient current was passed through the three cores in series to give a temperature-rise of about 20 deg. F. above the water. When steady conditions were reached the heating current was switched off and the fall of resistance with time was measured on a Kelvin low-resistance bridge, so that it was easy to deduce the exact resistance and thus the temperature of the cores at the moment of switching off. The test was carried out with the water at 60° F., 100° F., 140° F. and 175° F., the other conditions remaining the same, so that the results should be strictly comparable. It was found that the thermal resistance decreased with temperature in a regular manner, the ratio of the resistivities at mean temperatures of 69° F. and 183½° F. being 1·62. It was intended to carry out further tests to confirm this interesting result, but the pressure of other work has so far prevented this. In regard to the discrepancy between the electrostatic analogy and the thermal case when the loading on a three-core cable is eccentric, as described on page 546, one would like to know the

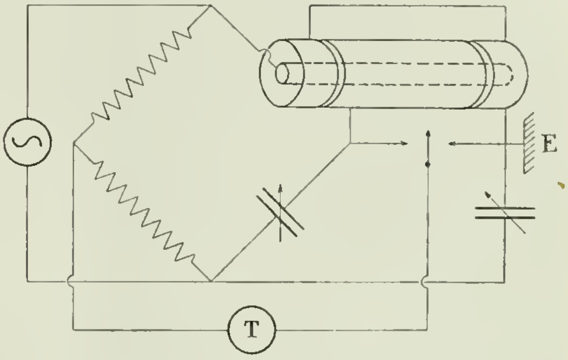


FIG. B.

temperatures of the cores and sheath. If the mean temperature of the dielectric were different in the two cases, the change in the thermal resistivity might account for the 10 per cent difference. There are two other factors worthy of consideration: (1) If the "worming," i.e. the material used for filling the spaces between the cores, was of jute, its thermal resistivity may have been different from that of the paper, and so the dielectric would not be homogeneous; and (2) the electrostatic analogy demands that the cores and sheath should be perfect conductors as compared with the dielectric. Taking the figures on page 534, the thermal resistivities of impregnated paper and lead are 500 and 2·9 respectively, giving a ratio of 172 : 1, and this is of a much lower order than in the electrical case. Thus, when the two cores were used for heating there would be a difference of temperature in the sheath, i.e. the surface of the sheath and possibly that of the idle core would no longer be isothermals. Both (1) and (2) would modify the distribution of the lines of heat-flow and so affect the comparison with the capacity tests. In Appendix III, in describing the electrostatic model, the trouble caused by end-effects is referred to. This can be overcome by providing the outer cylinder with guard-rings at either end, and using the Wagner double bridge * to measure the true capacity. The circuit is illustrated in Fig. B.

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

## NORTH-EASTERN CENTRE, AT NEWCASTLE, 12 MARCH, 1923.

**Mr. P. F. Allan:** The expression of the principal quantities in electrical measure, thus avoiding the use of conversion factors, is a particularly useful feature of the report. Criticism must be confined to the few errors of statement which are bound to creep into a work of such magnitude, and perhaps to one or two of the assumptions made. In general, I find myself in agreement, so far as my own experience and knowledge go, with most of these assumptions. It must be realized, however, that to make these figures of permanent value cable makers will need to be asked to guarantee the thermal resistance of their cables or the thermal resistivity of the insulating materials employed. This may have the effect of shutting out some foreign competition of a harmful nature. Also, it must not be forgotten that the high current-carrying capacities of many of the lower pressure cables cannot always be taken advantage of except for short lengths. While I realize that the Committee and the authors, in limiting the maximum temperature to 50° C. for cables laid in ducts, were guided by a mass of information not available to myself and other individuals, I do not think that they have quite made out their case for this particular assumption or decision. Mr. Fawssett in presenting the report mentioned that the 35 deg. C. rise applied to cables both in air and in ducts. It is not made clear in the report whether or not it is intended that the final temperature in air should be 65° C. or not. I am particularly interested in the air figures on account of their possible application to mining conditions, as they will form a useful basis for further investigation of the peculiar conditions applying in mining work underground. One effect of a report such as this will be to remove the excuse that there are no definite figures to go upon, and therefore to throw greater responsibility on engineers engaged in the design of distributing systems. They will be required to make proper allowance for all the varying conditions met with. On pages 519 and 538 the authors say that a large amount of data has been collected in respect of various countries, including India and Australia. They further state that "the Australian figures are not greatly higher than these," referring to British figures just quoted. I feel that these statements are really misleading, omitting as they do any reference to the moisture content and the other characteristics of the soil, and particularly in that they represent very small and (in the case of Sydney, Perth, Adelaide, and Calcutta) not very typical parts of the countries mentioned. It may be agreed that a very large proportion of the electrical development in these countries is centred in a few large cities, but due qualification should be made in the report in its final form, or otherwise mistaken assumptions may be made. I do not at all like the idea of obtaining information about these large and important countries through a single source, and that only an indirect one. It would have been much more gratifying to our fellow engineers in responsible positions abroad, many of whom feel that they are cut off from the activities of the parent Institution, if the Committee had asked the various Local Hon. Secretaries to send out a proper questionnaire to all the members resident in their territory, and I feel certain that the resulting information would have added materially to the value of the report. I am interested in the explanations given of the reasons for error in Russell's formula, and the limitations of its practical application. Will the authors be good enough to give a similar statement with regard to the reason of the error between the theoretical calculations of the value of $g$ and the actual experimental results obtained?

**Mr. C. Turnbull:** With low-pressure current we cannot usually run cables at a density which will cause them to heat unduly, as the drop of pressure becomes too great before that, but with extra-high pressure a different state of things takes place. Modern superstations require a pressure of 20 000 to 30 000 volts to enable them to transmit the current in cables of practical size. A 10 per cent pressure-drop, or more, is common enough with low-pressure supply, but a drop of 2 000 or 3 000 volts on a high-pressure cable would usually involve an impossible current density. This means that Kelvin's law does not apply to these, but that a strict watch must be kept on temperature: it will in fact be as necessary to study the heating of underground cables as that of conductors on generators and transformers. This brings us to the difficulty that soil conditions are not only difficult to predict but that they may vary by the running of other mains in the neighbourhood, mains which in some cases may belong to another authority. Where mains are to be run at the highest densities, it will be necessary to increase their section in places congested with a large number of other mains, e.g. where they enter the station or substations. I would suggest that the curves might in some cases be simplified by the use of logarithmic ruling.

---

* K. W. WAGNER: *E.T.Z.*, 1911, vol. 40, p. 1001; also S. BUTTERWORTH: *Proceedings of the Physical Society*, 1921, vol. 34, p. 8.

**Mr. J. Y. Hutchinson** (*communicated*): A satisfactory theoretical treatment of the heating of buried cables is very difficult and must involve some empirical matter, but it seems to me that a more straightforward consideration of the subject might be found than the one presented in the report. To my mind the whole question centres round the correct application of the fundamental formula $H = t_1/(S + G)$ in which $(S + G)$ should be the thermal resistance between two isothermals in the heat circuit and $t_1$ the difference in temperature between the *same* two isothermals. One of the isothermals will be the surface of the conductor and the other may be any isothermal within the ground. The values of $G$ and $t_1$ will vary according to the isothermal chosen, but for any value of $G$ there will be a corresponding value of $t_1$, referring to the same isothermal. Any value of $G$ will be useless for substitution in the formula without definite knowledge of the corresponding value of $t_1$. If $t_1$ be taken as the temperature-rise of the cable, then $G$ should be the thermal resistance of the heat circuit between the outer surface of the cable and the isothermal corresponding to the original temperature of the cable. This latter isothermal may be in the ground or, more likely, will cut the surface of the ground and be in the air. In this case part of the heat circuit will be in air, and $G$ must include the equivalent of the thermal resistance of the air. On the other hand, if $G$ refers simply to the thermal resistance of the ground then $t_1$ should be considerably lower than the rise in temperature of the cable, since the temperature even at the surface of the ground will be considerably higher than the initial temperature of the cable if isothermals cut the ground. It seems to me that the best treatment would be to ignore Kennelly's formula and to obtain a new empirical expression for the thermal resistance of the heat circuit between the outer surface of the cable and the isothermal corresponding to the initial temperature of the cable. If, when comparing practical results with theoretical results, $t_1$ were taken as the rise in temperature of the cable, then it would seem from the above that Kennelly's formula is more inaccurate than a 0·6 correction factor implies. The investigation of the distribution of isothermals, as described, is not altogether satisfactory, owing to the comparatively small size of the box and the use of a medium of high resistivity which results in isothermals entering the air on all four sides. The fact that the cable was vertical also affects the result to some extent, as the heat at the surface will not be so effectively dissipated by convection as in the case of a horizontal cable. The results of further investigation under varying conditions of depth and resistivity would be interesting.

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

## NORTH MIDLAND CENTRE, AT LEEDS, 20 MARCH, 1923.

**Mr. W. E. French**: I wish to confine my remarks to one or two points which seem to have an important bearing on the maximum carrying capacity of cables buried in the soil. When studying the Tables 3 to 14 for cables buried directly in the soil (and also the curves shown on the screen) one is immediately confronted with the great importance of the soil resistivity, $g$. According to these tables and curves the maximum current-carrying capacities of cables may be increased by 25 and even 50 per cent, the increase depending entirely on the resistivity of the soil surrounding the cables. A study of the curves giving $g$ as a function of the moisture of the soil and the quality of the soil, shows that $g$ may vary between 90 and 340 to 400, these figures also being quoted in Table 31 as the proposed British Standards or, rather, as the basis on which the British Standard cable loading will be based. On the other hand, some Continental writers on the subject quote 50 as a good average value for the soil resistivity. Therefore, the maximum current-carrying capacity of a cable is largely determined by $g$, which in turn depends on the nature and moisture of the soil in which the cables may be buried. I think that this rather represents one of the troubles which may be experienced in the use of the tables mentioned. The engineer responsible for the design of the network naturally desires to work his cables at their best current-carrying capacities and he must therefore have the fullest information regarding the resistivity of the soil through which his cables will pass. The method adopted for the determination of $g$, while perfectly valid in itself, appears to me rather to give confined laboratory results than to furnish figures more in accordance with the actual local conditions of the soil in which the cables are laid. The guard-ring method rather limits the information on $g$ to a few samples of soil. I have in mind an alternative method which was first proposed by Ångström, and later modified by Forbes and Kelvin for the determination of the thermal conductivity of the earth's crust; it is the method of periodic heating and cooling and can be made directly applicable to the determination of the thermal conductivities or resistivities. During the day the earth's surface is heated, and during the night is cooled; therefore a series of heat waves pass from the earth's surface to the interior. If the heat wave-length and its periodic time are known, the diffusivity (according to Kelvin the ratio of the thermal conductivity to the thermal capacity per unit volume) can be calculated, and from this the conductivities and resistivities could be deduced. If the periodic variations are uniform, and assuming that in any locality the soil may be considered to be reasonably uniform, then the heat-waves passing through the soil may be taken to be the same as with a bar periodically heated and cooled. Thermometers or thermo-couples buried at various depths would record the progress of the diurnal heat-waves; the wave-lengths could be determined and, assuming a simple harmonic function of the temperature, the diffusivity could be calculated for the expression $K = \lambda^2/(4\pi T)$, where $\lambda$ = wave-length, and $T$ = periodic time of the heat-waves, and from this the resistivity could be found. This method if standardized would lead to a far more universal investigation of $g$, and even provide the engineer with a means of conducting his own thermal survey of the soil through which his cables have to pass. When discussing the first report I pointed out the desirability of investigating the heating of cables with regard to the thermal time-constants, and so establishing data and a method by which the thermal characteristics of a cable could be predicted. I understand that the authors have gone into this question, and that they are reserving this question for a separate publication. I should therefore prefer to reserve any remarks which I may have to make on this point until I have had an opportunity of reading this further paper.

**Mr. J. W. J. Townley**: One of the difficulties which I foresee in the use of the tables is the determination of the value of $g$, the thermal resistivity of the soil. In this district, with a fairly heavy clay soil, I think that the value of $g$ might be safely taken at 180, and it would be very desirable indeed if a table could be prepared giving an average value for $g$ for various districts throughout the United Kingdom. This work might well be undertaken by the Local Centres, and could be published with the tables so that an engineer working in a strange district would find in them a safe average value of the thermal resistivity of the local soil. No doubt wide variations in the soil will occur on any particular route, but it will be necessary to determine average values for everyday practice, and it should be remembered that the maximum-current tables given in the report are based on relatively low temperature-rises, so that the factor of safety is high. Another point which has occurred to me is that where voltage-drop conditions will allow of cables being loaded to the maximum values given, in many cases network boxes, fuse pillars and other accessories will require to be replaced to take full advantage of the maximum load capacity of the cables which, on past standards, will be quite inadequate for the new ratings. Mr. Melsom has pointed out that armoured cables have a higher carrying capacity than similar cables unarmoured. Were the armoured cables he used of the usual form, in which the armouring is laid over jute or Hessian tapes and jute-served or Hessian-taped overall? It would appear that a marked difference would be effected in the radiating capacity of a cable by putting the armouring directly in contact with the lead, but the report does not distinguish between these two forms.

**Mr. R. M. Longman**: The subject of this report is of special interest to me, as it was my good fortune in 1905 and 1906 to assist Mr. Fawssett in the original tests carried out in this country, and it was at the completion of these tests that I noted the first reference to the work of the V.D.E. on the subject, as published in *Science Abstracts*. These tests were carried out on 6 000-volt cables and no attempt was made to take into account the effect of moisture in the soil, but on plotting the figures obtained alongside the figures given in the paper a remarkable close agreement is shown with the figures for $g = 180$. I have little doubt that the figures thus obtained have largely formed the basis on which many engineers have worked for the past few years, with probably only a very slight idea of their origin. I cannot recollect any case of cables at this loading having suffered any deterioration or damage; I am aware of a 20 000 volt cable which had been run at much higher loading for long periods and which on the removal of a short length, not due to breakdown, showed signs of deterioration, the impregnating oil having become dry and patchy. This may be looked upon as the beginning of the end, as hot spots and puncturing of the layers of paper may occur which are no longer healed up by the action of the impregnating oil; even so, the cable will probably last for many years, particularly if not overloaded. Have the authors experienced any similar cases? With regard to the samples of soil tested, I believe these have been chiefly taken when laying new cables. Have samples also been taken along cable routes where the cables are heavily loaded? The tendency in such cases where a certain amount of heat is generated is to find the soil drier than is otherwise the case. Have any tests been made along a heavily loaded cable route to determine the isothermal lines by taking simultaneous temperatures of the soil immediately above the cable and a short distance, say 18 in. or 2 ft., on each side, the thermometers in each case being placed at equal depths in the soil, say 2 in.? Are the V.D.E. figures given in the report the same as those which appeared in *Science Abstracts* in 1905 or 1906? With reference to the bunching or grouping of cables such as is often necessary when leaving a power station or substation, a considerable gain in capacity may be obtained by the careful arrangement of the same by interspersing pilot or telephone cables or lightly loaded cables between those more heavily loaded. Attention to such a point may easily increase the capacity of the cables by 10 per cent. In some cases where excavation costs are high it may be advisable to provide more copper, the cost of excavation being balanced against the extra cost of cable. A type of laying to which the authors have not alluded and which has been extensively used, is the laying of cables in iron troughing which is then filled in with pitch or bitumen. Can they furnish information as to the permissible loading in such cases? Such cables are not armoured and this method of laying cannot be described as the "solid" system. Many such cables are arranged alongside a wall, for instance in tunnels, under bridges and in railway cuttings, and unfortunately in many cases they are fully exposed to the sun.

**Mr. W. B. Woodhouse**: The work that the Research Association has done in this matter is of very great value because it will help us to reduce the cost of distribution in a number of cases. In a paper * which I read some little time ago, I pointed out that in the majority of cases the application of the economic law of minimum total annual cost of distribution showed that the economical current rarely reached the limiting value for the cable, but even so it is of value to know in every case the practical limit of loading. Users of cables have to consider in practice that their cables are laid in different soils and under different conditions, e.g. where they run in substations or pass through ducts. It is usually impracticable to cut the cable and introduce a short length of larger cable. Where the cooling effect is reduced in this way the possibility of introducing additional means of radiation is worth considering. For example, the trench might be packed with some material of high heat conductivity, the cable might be fitted with radiating fins, or water cooling might be adopted. There are many ways of dealing with this problem and our more accurate knowledge of the heating is of benefit. An accurate indication of the average temperature of a long length of cable is easy to obtain, but the important matter is to determine the maximum temperature at a hot spot. The research has brought out in an interesting way the relative cooling of cables laid at different depths. There has been a tendency to exaggerate the effect of laying cables in deeper trenches. The report shows a comparatively small difference for practical depths, and even this difference may be substantially modified by the additional percentage of moisture in the deeper trenches. The results should emphasize the fact that the grouping of cables in ducts is bad, not only on account of the reduced radiation, but also because of the smaller degree of safety in case of breakdown.

---

* *Journal I.E.E.*, 1922, vol. 59, p. 85.

| Nature of Soils | Nature of Surface | State of Surface | Date taken | Depth taken | Moisture |
|---|---|---|---|---|---|
| | | | | | Per cent |
| Yellow clay, much sandstone .. | Flags | Damp | 22/11/21 | 3 ft. 0 in. | 13·7 |
| Stiff clay .. .. .. .. | Square sets | Damp | 22/11/21 | 4 ft. 0 in. | 13·5 |
| Shale and soft rock .. .. | Flags | Damp | 1/12/21 | 1 ft. 6 in. | 13·5 |
| Stiff clay .. .. .. .. | Flags | Damp | 1/12/21 | 1 ft. 6 in. | 12·4 |
| Clay .. .. .. .. | Unmade | Wet | 1/12/21 | 1 ft. 6 in. | 25·0 |
| Sandy soil and sandstone .. | Flags | Damp | 1/12/21 | 3 ft. 0 in. | 10·4 |
| Sand and clay in thin layers .. | Flags | Damp | 23/2/22 | 5 ft. 0 in. | 18·4 |
| Clay .. .. .. .. | Flags | Damp | 8/12/22 | 4 ft. 0 in. | 13·2 |
| Sandy soil and sandstone .. | Flags | Damp | 8/12/22 | 2 ft. 3 in. | 9·7 |
| Soil, ashes and cinders .. .. | Tarmac | Damp | 23/2/23 | 2 ft. 3 in. | 15·0 |
| Soil, ashes and cinders .. .. | Ashes | Damp | 23/2/23 | 1 ft. 9 in. | 30·0 |
| Clay and sandstone .. .. | Flags | Damp | 23/2/23 | 1 ft. 6 in. | 14·6 |
| Stiff dark clay .. .. .. | Unmade | Wet | 3/3/23 | 1 ft. 8 in. | 14·5 |
| Clay with cinders and shale .. | Flags | Dry | 13/3/23 | 2 ft. 6 in. | 21·5 |
| Dark clay and soil .. .. | Square sets | Dry | 13/3/23 | 4 ft. 6 in. | 19·6 |
| Dark soil and refuse .. .. | Flags | Dry | 13/3/23 | 2 ft. 9 in. | 33·2 |
| Sandy clay and sandstone .. | Flags | Dry | 13/3/23 | 1 ft. 8 in. | 13·0 |
| Soil and clay .. .. .. | Flags | Dry | 15/3/23 | 3 ft. 6 in. | 18·8 |

**Mr. W. R. T. Skinner**: I have compared the figures given by the authors with those in the I.E.E. Wiring Rules. The figures are not strictly comparable for all classes of cables and the I.E.E. tables were not intended for buried cables, but, in default of other loading tables, the I.E.E. Wiring Rules have formed a basis for cable ratings and consequently the comparison may be of some use. The comparison is best made by considering the values of the thermal resistivity of the ground to which the ratings given in the I.E.E. tables correspond. One finds that for 11 000-volt three-core 0·25 sq. in. cables the equivalent value of $g$ is 230, increasing to 340 in the case of a 0·075 sq. in. cable. For cables smaller than 0·075 sq. in. the equivalent value of $g$ is greater than 340. Again, for 2 200-volt three-core cables, one finds that for a 0·25 sq. in. cable the equivalent value of $g$ is 280, increasing to approximately 340 for a 0·10 sq. in. cable. For sizes below 0·10 sq. in. the equivalent value of $g$ is greater than 340. It is clear from these figures that, if the I.E.E. tables have been used for buried cables of the types considered, the loading has been well on the safe side for all but the worst conditions of the ground, from the point of view of thermal resistivity. With regard to the curves of maximum ground temperature, I should like to know whether it would not be an advantage to show the highest maximum temperatures occurring in the past 12 years, instead of the average maxima, or whether this curve is covered by the two curves for the exceptional years 1911 and 1921. I notice that the difference between the current-ratings for cables used on systems with an earthed centre point and those used on systems with an unearthed centre point, is only some 4 per cent at the most. In view of the fact that some speakers have already mentioned the possibility of simplifying the tables, if that difference of 4 per cent is not justified by the assumptions on which the tables are based, could not the two sets of tables be merged into one ?

**Mr. H. P. Bramwell** (*communicated*): Since the publication of the Preliminary Report, I have carried out a number of tests of the moisture content of the soil in the Bradford district. The results are given above, tabulated in a form comparable with those for the Newcastle district, given in Table 60 in the present report. These figures are not complete, and I am making further tests, as it will only be possible to make full use of the valuable information summarized in the report if one is able to plot a thermal resistivity ($g$)/moisture content curve for the different kinds of soil found in the district, and also to have a reliable figure to take as the average minimum moisture content throughout the year.

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

## NORTH-WESTERN CENTRE, AT MANCHESTER, 20 MARCH, 1923.

**Mr. H. A. Ratcliff:** Most of my mild criticisms on the Preliminary Report are still more or less applicable to the present report. I then advocated starting with the super-tension cables on the principle of the greater including the lesser, for if we are satisfied that the 33 000-volt cables are safe the others may be said to look after themselves. The authors appear to have taken certain arbitrary values for the permissible working temperatures of the conductors, and two specific cases have been dealt with, viz. cables laid direct in the ground, and cables drawn into ducts. Having selected those arbitrary values, then, partly by calculation and partly by experiment, they have arrived at the loadings of the several cables which result in those conductor temperatures being attained. When the theoretical and experimental results did not agree they appear to have adjusted them until they did agree. There is no doubt that the first consideration is the maximum safe working temperature; that is really the crux of the whole matter, and the rest follows as a matter of course. I am inclined to think that in many cases the maximum safe temperature will never be attained, because for other reasons the cables concerned will never be loaded up to the values necessary to produce it. No attempt is made in the report to define the maximum safe temperature, and I should be glad if the authors in their reply would give rather more detailed reasons for the selection of the particular working temperatures, viz. 65° C. and 50° C., respectively. To what extent, in their opinion, do those temperatures allow for a reasonable factor of safety, such an essential feature of sound engineering work? The report contains a number of tables giving the permissible loadings for all the cables scheduled in B.S.S. No. 7, and for various pressures up to and including 11 000 volts, but if the tables are examined carefully it will be found that in most cases the differences between the loadings for the several pressures are very small. Such differences as occur appear to be within the limits of error which may naturally be expected to arise from the many variables with which the authors have had to contend. In any case the variations for different voltages are less than those resulting from such a comparatively indeterminate quantity as the resistivity of the ground. The most notable differences are between the loadings for the 2 200- and 3 300-volt cables laid direct in the ground, but, for some not very obvious reason, when the cables are in air there is very little difference between the loadings for the same two pressures. We have been laying 33 000-volt cables in Manchester for some years. When we first purchased them there were very few data available relating to safe loadings and working temperatures, but from such data as were available, and the results of experiments carried out at the cable makers' works, we arrived at the figure of 60° C. for the safe working temperature of 33 000-volt cables after allowing a margin for contingencies. The permissible loadings worked out on the basis of that temperature are very little different from many of the figures given in the report, having regard to the fact that we had no definite information relating to the resistivity of the ground. The following are typical values for the loadings of three-core, 33 000-volt cables: 0·1 sq. in.—165 amps.; 0·15 sq. in.—210 amps.; 0·25 sq. in.—280 amps.; 0·30 sq. in.—315 amps.; and 0·35 sq. in.—345 amps. Not having definite information as to the relative effect on the cable temperature of direct laying and drawing into ducts, it was decided to reduce the current density in cables drawn into ducts in the vicinity of the generating station and substations. In other words, the section of the cable was increased in those particular positions. The most noticeable difference between "duct" and "direct laid" conditions referred to in the report is the arbitrary one of 15 deg. C. between the permissible working temperatures. This temperature difference is of considerable importance, because it appears to represent a difference of about 12 per cent between the actual loadings of the cables under the respective conditions. The reduction in the maximum permissible temperature in the case of cables drawn into ducts appears to have been based mainly on mechanical considerations, and I should therefore like to have the authors' opinion of its applicability or otherwise to wire-armoured cables, since the best modern practice is to employ a wire armouring on lead-covered cables when they are to be drawn into ducts. One remarkable fact which emerges in this connection is that when cables are drawn into ducts the resistivity of the ground is more or less immaterial, and consequently the temperature conditions of the cable are the same over a comparatively large range of ground resistivity. Probably the most important feature of the report is the information relating to the short-time or emergency ratings, because as a rule in actual practice it is only under emergency conditions that cables are deliberately overloaded. Owing to the breakdown of a cable, for instance, it may be necessary to overload other cables to a very considerable extent for an hour or two, but in view of the information given in the report the risk attending such temporary overloading is negligible. The ultimate limits of loading will, I think, be fixed by considerations of either copper loss or dielectric loss, according to the working pressure of the cables. More information on the subject of dielectric losses is very desirable, as at present we are somewhat in the dark as to their cause and effects, and, consequently, there is a tendency to make them somewhat of a bogy. One other limitation to the permissible loadings arises from the effects of contraction and expansion. At one time these effects were considered to be very troublesome, but I am inclined to the view that they are not so serious as is usually supposed, and the figures given in the report bear that out. I have come to the conclusion that many of the troubles due to contraction and expansion are the result of bad joints. Some recent experiments have shown that the ultimate strength of a well-made joint is comparable with that of the conductor, and therefore it is not very obvious why trouble should be expected with joints. The simplest joint on a three-core cable is the one made with plain sleeves or sweating ferrules, and tests have shown such a joint to be strong enough for all practical purposes, provided that the ferrules are fitted with grub screws. Although they do not in themselves contribute materially to the strength of the joint, the grub screws are very essential because they serve to maintain the ferrules and the conductors in rigid and intimate contact during the period when the solder is setting. The report contains much information relating to ground isothermals and temperature gradients, but only so-called virgin ground has been considered, and it would be interesting to know to what extent the various curves and formulæ are applicable to the ground in a large city under the road surface of which there is usually a miscellaneous collection of gas, water, and Post Office pipes, sewers, and even steam pipes and cellars. Another very important feature of the report is the experimental work relating to cables in multi-way ducts. The largest duct referred to is a six-way one, but I know of an 80-way duct, and I am at times inclined to wonder what are the conditions prevailing in the centre of such an extensive duct line. I was rather surprised to see that the three-core cables had the same temperature-rise when heated by the passage of either direct or alternating current. That result does not seem to be quite in accordance with general experience. The usually accepted figure for the increase in the $I^2R$ losses, due to the eddies in the lead sheath, is 5 per cent. It may be possible, however, that a 5 per cent loss in the sheath has not very much effect on the maximum temperature of the cores. In the case of single-core cables now used to a considerable extent for extra-high-pressure circuits, the effect of the sheath losses becomes of very great importance. A figure of 10 per cent has been put forward for sheath losses in such cases, but actually it depends to an enormous extent on the spacing between the separate conductors. Recent experiments have shown that a sheath loss equal to 15 per cent of the core loss is about normal for close spacing, but the value rises very rapidly as the spacing is increased beyond 6 inches.

**Mr. W. J. Medlyn:** The report deals with difficulties caused by the expansion and contraction of power cables, due primarily to the heating effect of the currents transmitted. I understand that cases occur where power cables laid in pipes or ducts on a slope have a tendency to slip downhill when they expand, with the result that they are heavily strained at the upper end each time that contraction takes place on cooling, after the current is shut off or reduced in strength; and, apparently, repetition of the strains may cause fracture of the cable. No doubt such cases have come under the notice of the authors, and it would be interesting to know whether any satisfactory method of overcoming the difficulty has been devised. In this connection I should like to mention one point where there is some relationship between power cables and telephone cables. In a few cases in the Manchester and Liverpool district some of the lead-covered trunk telephone cables, measuring about 3 inches in diameter, laid in stoneware ducts of the type illustrated in Fig. 20, have shown a tendency to creep after the jointing has been completed. The joints in these cables are made in manholes in which the ducts are terminated. In a number of cases the pull has been sufficient to stretch the cable and force the joint into one end of the duct, thus causing the lead sheath to be fractured. The cases have generally occurred, not on pronounced slopes, but on fairly level ground. The exact cause of the trouble has not been definitely ascertained, but probably it may be due partly to temperature variation, and partly to the effects of the vibration caused by road traffic, the cable movement being generally in the same direction as the traffic on the particular side of the road concerned. The heating effect of the minute currents passing through the cable is, of course, negligible, and the temperature variations must therefore be due to atmospheric changes in the different seasons of the year. From conductor-resistance tests which have been made on some of the telephone cables in Lancashire it is calculated that there was a temperature variation of something like 11 deg. F. to 14 deg. F. as between summer and winter. In one case the temperature indicated on a thermometer placed in a duct 10 yards from the manhole was 65° F. in August as compared with 46° F. in November, a difference of 19 deg. F. I should be glad to know whether the authors, in the course of their research work, have included any observations of temperature effects in underground cables due to ordinary atmospheric changes, and, if so, how their figures compare with the results which I have mentioned.

**Mr. A. B. Mallinson:** The authors have referred to three systems: Cables laid in the air, cables laid in ducts, and cables laid direct in the ground. Under what rating would they classify cables laid solid in bitumen in wooden troughs, and cables drawn into fibre conduits? Are these to be classified as cables laid direct in the ground or as cables drawn into ducts? Have the authors done any experimental work on cables of different makes? It is only natural to assume that different makers sometimes employ different insulations, and that will have an effect upon the figures given in the report. On page 537 the interesting fact in cable laying is referred to, that in many cases a cable trench will for years act as a drain for the surrounding country. This is not often realized. It is very refreshing to hear the authors speak of cables loaded up to the limits permissible by heating. At a recent meeting at this Centre the advocates of automatic substations commented on the fact that most cables were not nearly fully loaded, and that there was no fear of them getting hot for reasons other than the current loading of the cables.

**Mr. B. Lakeman :** I should be glad of some further information in regard to Tables 3 to 27. I am surprised that in the report the loadings of cables in the ground and in air are based upon two distinct temperature-rises, viz. 50 deg. C. and 35 deg. C. Do the authors propose to reduce the results to a common basic temperature-rise when issuing the final form of the results of their experiments ? I consider that the usefulness of the tables would be thus enhanced.

**Mr. A. R. Porter :** Mr. Ratcliff has mentioned 80-way ducts in Manchester ; these, I think, consist of 80 single-way fibre conduits laid in concrete. I should imagine that with a nest of single-way ducts laid either direct in the ground or in concrete, the temperature-rise would be much less than in the case of the multiple ducts illustrated in the report. In the former case there is a much greater space between the ducts than is afforded by the comparatively thin walls of multiple stoneware, and it seems possible that practically the conditions given for a single-way duct line may be approached. It is known that a sudden and intense rise of temperature due to a short-circuit may be rapidly conducted throughout a multiple duct similar to that illustrated, tending to destroy the other ducts. I believe that this is not the case with the nest construction mentioned, and it therefore seems probable that the conditions of temperature-rise would be similarly modified. Have the authors carried out any tests of these conditions ?

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

## SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 4 APRIL, 1923.

**Mr. A. M. Taylor :** In the investigation, in Appendix III, upon the relation between thermal resistance and electrostatic capacity, the comparison between the experimentally determined electrostatic capacity and the capacity as determined by Russell's formula and also by Mie's formula, and the investigation of its relation to the thermal resistance of the cable, are particularly interesting. In a recent paper * I pointed out that the reciprocal of the capacity (termed by Karapetoff the "elastivity") is related to the geometrical dimensions of the cable in a precisely similar way to the thermal resistance, and I am glad that the authors emphasize this point. The remarks on page 541 relating to the difference between the expansion of the armouring of the cable and that of the lead sheathing of the copper would indicate that there are forces tending to buckle the copper conductor directly a point of minimum mechanical strength is reached. This would occur where the cable approached a junction box, and might take place in the junction box itself. In one case which came to my notice the copper had been quite crushed up and forced into connection with the box itself by this action. The tremendous forces that obtain must result either in the armouring being inordinately strained or the copper being unduly compressed, and it is not inconceivable that, due to the worming of the three copper conductors, a tendency to sudden bending might occur in parts of the cable itself which would be sufficient, even though unnoticeable, to crack the insulation and start a weak point which would develop into a fault. This points to the advantage of, if possible, doing without the armouring altogether, a course which was adopted in the Gennevilliers cables. I should like some more information on the subject of six-conductor cables, particularly of the size consisting of six 0·185 sq. in. cores used as a split-conductor cable, corresponding to an area (per phase) of 0·37 sq. inch. Several such cables were used on the Birmingham system and any information as to the possibilities of increased current-carrying capacity would be most welcome. In Table 16 a current of 328 amperes is given for a 0·25 sq. in. cable (concentric and armoured), while in Table 21 a current of 344 amperes is given for a precisely similar cable, with the difference, however, that the latter was insulated for 11 000 volts whereas the former was insulated for only 660 volts. One would have expected that the thermal resistance of the 11 000 volt cable would have been much higher than that of the 660 volt cable, demanding a very much smaller current, rather than that a larger current would have been permissible. Will the authors explain this point ? In Table 28 a figure of 620 is given for the resistivity of cable No. 3, and a figure of 1 060 for the resistivity of cable No. 4. There seems to be no obvious reason for this great difference. Again, it is stated on the same page that "examination of the experimental values for different types of cable showed that generally the lower-pressure cables had a thermal resistivity somewhat greater than the higher-pressure cables," and the remarks that follow seem to suggest that this is due to questions of cost. I should like to know whether it was in any way due to the fact that with the higher insulations there was a much greater distance through which impregnation had to take place, and whether the impregnation was possibly less perfect in the higher-voltage cables. In Table 39 the figure of 172 amperes is given for the safe current for a six-core 0·1 sq. in. cable. I would remind the authors that in Table 2 of the previous report the safe current for a precisely similar split-conductor cable was given as 284 amperes per core. I think that the latter figure was probably wrong, but I should like to know for certain that this is so, as the discrepancy is otherwise very serious. On page 546 it is stated, in dealing with triple-concentric cables, that if the load were assumed to be carried by the two inner conductors only, the current for a given temperature-rise would be 5 per cent less than that for the "equivalent" size of concentric cable with two conductors only. What would have been the result if the innermost and outermost conductors had been considered, the intermediate conductor carrying no current ? I am interested in a cable in which varying currents are carried in the different intersheaths, and my impression is that the greater the amount of heat that can be liberated towards the circumference of the cable, the lower will be the temperature of the innermost core. The expression "equivalent" used by the authors should also be defined. Do they mean by this the *same* cross-section for each of the two "outer" cores, or a cross-section such that the same power can be conveyed with the same *total* amount of copper at an equal voltage across the "outers"? In Table 1 are given particulars requiring further elucidation, and I am of opinion that the figures in heavy type, viz. 340, 180, 120 and 90 should preferably be, 227, 120, 80 and 60. I should like to see Equation (7) (page 523) extended in such a manner as to embrace triple-concentric cables in which there are various relations between the current in the central core and those in the outer cores.

---

* "The Possibilities of Transmission by Underground Cables at 100 000/150 000 Volts," *Journal I.E.E.*, 1923, vol. 61, p. 220.

**Mr. H. W. Blades:** It is very interesting to note from actual tests that there is no appreciable increase of heating in a three-core cable when loaded with three-phase current of varying periodicities, as compared with that occurring with direct current. One would naturally expect that the skin effect and the eddy currents in the lead sheath would have affected the results of the test to a certain degree. In dealing with the expansion of cables, an instance occurred a short time ago where a number of cables under abnormal war conditions gradually slipped for a distance of 4 ft. down a long gradient for a total distance of approximately 500 yards, but by taking advantage of the expansion of the cable when loaded, and by means of suitable clamps and straining devices, these cables were persuaded to creep uphill against the stiff gradient until they were back again in their original position. This was, of course, accomplished whilst the cables were carrying full load. On page 541 it is stated that "a cable drawn into a duct is free to move lengthways along the duct and cause injury to the lead by abrasion." From observations and tests on a large conduit system the chief trouble was found to be, not so much the question of the abrasion of the lead in contact with the duct, but how to accommodate the expansion of the cables and so prevent ripples in the lead and cracked plumbs, etc., in the joint pits. The linear expansion resulted in a longitudinal movement of the cable at the bell mouth, but by suitable bends in the cable at the joint pit this longitudinal movement was changed into a lateral movement of the joint box. The joint boxes are mounted on special cradles, and these are free to move in a transverse direction. Tests showed that these joints were in a state of continual movement. These joints have been working successfully for several years in this manner and there are no signs at all of the deterioration of the lead.

**Mr. W. E. Groves:** The information in the report is exactly what the mains engineer needs. It is most useful in stating concisely the factors to be reckoned with in assessing the rating of cables. Although the effects of the various conditions or circumstances of cable-laying are in most cases what were to be expected, the precise information is most useful in fixing the degree of importance to be given to each governing factor. In some instances, however, the experiments give results which are not only enlightening but also quite unexpected. As the permissible current loading is generally governed by the maximum temperature which can be attained without damage to the dielectric, it is hoped that more definite information will be forthcoming on this point. Meanwhile, the limits given will be in the mind of the engineer, who will realize that they must necessarily be safe as they are stated to be permissible in a report to which great weight will be attached. The thermal resistivity of the dielectric will obviously be constant throughout a cable length, but in considering a long run of main the safe loading will, from the point of view of thermal resistivity, depend on the worst patch of ground that it passes through. Consequently, in determining the load rating of the cable before laying, the least favourable conditions must be assumed. In this connection, one would expect that the nature of the paving would affect the moisture content of the ground. Modern methods of treatment of roadways render the surface practically impervious to moisture, and the surface water is much more thoroughly drained to the sewers. It is interesting to note that the mechanical strains due to expansion are considered among the limiting factors. Considerable ingenuity has been brought to bear on the countering of these effects and it is to be hoped that ultimately the permissible temperature will be limited solely by the effect on the dielectric properties of the insulation. This limitation due to expansion is emphasized in the writing down of the permissible temperature of cables in conduits by 15 degrees C. in order to avoid abrasion of the lead. This appears to be hardly justified if the internal surface of the conduit is smooth and well-lubricated when the cable is drawn in. At any rate it seems too high a price to pay and one would rather risk a little, as the damage would be more local than that caused to the cable by overheating of the dielectric. Conduits are an unfortunate necessity in many cases and it is both interesting and surprising to learn that the experiments show that the temperature of the cable is not materially affected by the relative dimensions of cable and conduit. The publication of the results of exhaustive research, and formulæ for calculating the effect of practically all possible conditions of mains laying, should result in more scientific practice than has hitherto obtained.

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

# REPORT OF THE COUNCIL FOR PRESENTATION AT THE ANNUAL GENERAL MEETING OF 31 MAY, 1923.

## CONTENTS.

Par.
Accounts .. .. .. .. .. .. .. 47
Advertisements in *Journal* .. .. .. .. 31
Agriculture, Electricity in .. .. .. .. 38
American Institute Convention .. .. .. 24
Appointments Board .. .. .. .. .. 29
Associazione Elettrotecnica Italiana .. .. 25
Benevolent Fund .. .. .. .. .. 46
British Manufactured Goods .. .. .. .. 40
Building .. .. .. .. .. .. 10
Bye-Laws .. .. .. .. .. .. 1
Centres .. .. .. .. .. .. .. 13
Conversazione .. .. .. .. .. .. 20
Deaths .. .. .. .. .. .. .. 9
Dinner .. .. .. .. .. .. .. 21
Distinctions .. .. .. .. .. .. 6
Electricity Regulations Committee .. .. .. 37
Electrotechnical Commission, International .. 45
Engineering Joint Council .. .. .. .. 42
Examinations .. .. .. .. .. .. 4
Faraday Medal .. .. .. .. .. .. 7
Honorary Members .. .. .. .. .. 5
Honours .. .. .. .. .. .. 6
Informal Meetings .. .. .. .. .. 17
Institution, Organization of .. 48 and Appendix D
Irish Free State .. .. .. .. .. 39
*Journal* .. .. .. .. .. .. .. 30
Koninglijk Instituut Van Ingenieurs .. .. 26
Libraries for Local Centres .. .. .. .. 14
Library, Institution .. .. .. .. .. 27
Liquidation .. .. .. .. .. .. 2
Local Honorary Secretaries Abroad .. .. 15
Meetings .. .. 11, 12, 17, 22 and Appendix B
Membership .. .. .. 3 and Appendix A
Model Conditions for Contract .. .. .. 34
Museum .. .. .. .. .. .. .. 28
Papers .. .. .. .. 11 and Appendix C
Portraits of Past-Presidents .. .. .. 23
Premiums .. .. .. .. .. .. 11
Proving House .. .. .. .. .. 35
Registration of Electrical Contractors .. .. 36
Representatives .. .. 48 and Appendix D
Research Association, British Electrical .. .. 43
Scholarships .. .. .. .. .. .. 19
*Science Abstracts* .. .. .. .. .. 32
Standards Association, British Engineering .. 44
Students' Sections .. .. .. .. .. 18
Sub-Centres .. .. .. .. .. .. 13
Summer Meeting .. .. .. .. .. 22
Technical Schools, Training in .. .. .. 41
War Memorial .. .. .. .. .. .. 8
Wireless Section .. .. .. .. .. 16
Wiring Rules .. .. .. .. .. .. 33

## REPORT.

The Council, at the Fifty-first Annual General Meeting of the Institution of Electrical Engineers, present to the members their Report for the year 1922–23, covering approximately the period 1 April, 1922, to 31 March, 1923, and, in doing so, desire to put on record their gratification at the continued progress of the Institution.

### (1) Bye-Laws.

The Bye-Laws for the Chartered Institution which were approved at a Special General Meeting of Corporate Members held on the 23rd March, 1922, received the sanction of the Lords of the Privy Council on the 1st June, 1922. Members who have not already received a copy can obtain one on application to the Secretary.

### (2) Liquidation of Old Institution.

The process of transferring to the Chartered Institution the property of the old Institution, including the trusts in connection therewith, has proved more protracted than had been anticipated, chiefly owing to certain provisions in some of the trust deeds necessitating, on the dissolution of the old Institution, steps being taken to ensure that these trusts and the benefits under them should pass to the Chartered Institution. For that reason, the final winding-up must necessarily be postponed a short time longer until the whole of these trusts and benefits have been transferred to the new Institution.

### (3) Membership of the Institution.

The changes in the membership since the 1st April, 1922, are shown in a table which will be found in Appendix A.

The following table shows the growth of membership for the last few years :—

| Year | Membership | Increase or Decrease |
|---|---|---|
| 1913 | 7 084 | — |
| 1914 | 7 045 | − 39 |
| 1915 | 6 811 | − 234 |
| 1916 | 6 676 | − 135 |
| 1917 | 6 613 | − 63 |
| 1918 | 6 667 | + 54 |
| 1919 | 7 023 | + 356 |
| 1920 | 8 146 | + 1 123 |
| 1921 | 9 449 | + 1 303 |
| 1922 | 10 275 | + 826 |
| 1923 | 10 911 | + 636 |

It will be seen from the above that, while the decrease in membership during the war period was 471, the increase since the war has amounted to 4 298.

The Council have noticed with satisfaction the practice of some employers of stipulating Corporate Membership of the Institution as a qualification for vacant positions, and urge its adoption by all employers.

### (4) Examinations.

The Associate Membership Examination was held in April and October, 1922, in London, Chatham, Birmingham, Manchester, Newcastle-upon-Tyne and Cardiff, and also abroad in New Zealand, South Africa and Australia. The candidates examined included a number of officers of the Corps of Royal Engineers who sat for the examination for the purpose of qualifying for "Engineer Pay."

A certain number of candidates submitted theses and papers during the year in lieu of the examination.

For the purpose of qualifying for "Signal Pay" Officers of the Royal Corps of Signals were examined by the Institution in the "Theory of Electrical Military Signalling" at the Signal Service Training Centre, Maresfield Park Camp, Sussex, in August, 1922, and February, 1923.

### (5) Honorary Members.

The Council have pleasure in recording that, as announced at the Ordinary Meeting of the 16th November, 1922, they have elected Professor John Ambrose Fleming, M.A., D.Sc., F.R.S., to be an Honorary Member of the Institution. The number of Honorary Members now stands at 10.

### (6) Honours and Distinctions Conferred on Members.

Since the last Annual Report the following honours have been conferred on members:—

**Baronetcy.**

Drummond, Brig.-Gen. H. H. J., C.M.G. (Associate).
Sutton, George (Member).

**K.B.E.**

Lewis, H. D. W. (Member).

**Knighthood.**

Hughman, E. M. (Associate).
Manville, E., J.P., M.P. (Member).

**C.B.**

Wray, Capt. T. H. Roberts, O.B.E., R.N.V.R. (Associate Member).

**C.V.O.**

Hussey, Major W. C., R.E. (Associate).

### (7) Faraday Medal.

To commemorate the 50th anniversary of the foundation of the Institution (under the name of the Society of Telegraph Engineers), the Council decided last year to establish a "Faraday Medal" in bronze to be awarded by the Council not more than once a year for "notable scientific or industrial achievement in Electrical Engineering or for conspicuous services rendered to the advancement of Electrical Science without restriction as regards nationality, country of residence or membership of the Institution."

The Council selected for the first award of the medal Mr. Oliver Heaviside, F.R.S., who, unfortunately, owing to ill-health, was unable to attend a meeting of the Institution to receive the medal, which was personally presented to him by the then President, Mr. J. S. Highfield, at Torquay on the 9th September, 1922.

The second award of the medal has been made by the Council to the Hon. Sir Charles Algernon Parsons, K.C.B., F.R.S.

### (8) War Memorial.

The unveiling and dedication of the War Memorial in the Institution Building in memory of the members of the Institution who lost their lives in the War of 1914–18 took place on Wednesday afternoon, 28th June, 1922. The Memorial is in the form of two bronze panels, containing the names of 162 fallen members, designed by the Institution's architect, Mr. H. Percy Adams, F.R.I.B.A., and modelled by The Birmingham Guild, Ltd., and fixed respectively on the East and West walls of the Entrance Hall.

A full account of the ceremony is contained in the *Journal*, vol. 60, p. 948.

The War Memorial Book containing the biographical notices and portraits of the fallen members will, it is hoped, be published in the course of the year.

Out of the balance of the above Fund it has been decided to establish two scholarships, each of the value of £50 per annum and tenable for three years, to provide for the education of children of those members of the Institution who were killed or permanently disabled in the War.

### (9) Deaths.

The Council have to deplore the death of the following 48 members of the Institution during the year.

*Honorary Member.*

Bell, Professor Alexander Graham.

*Members.*

Claremont, E. A.
Craig, J. H.
Darby, J. C. H.
Dewar, Prof. Sir James, M.A., F.R.S.
Fraser, J.
Gavey, Sir John, C.B.
Godfrey, W. B.
Kapp, Prof. Gisbert.
Miller, H. W.
Robinson, M. H.
Sharp, S.
Suckling-Baron, A. I.
Talbot, F. F.
Trouton, F. T., M.A., D.Sc., F.R.S.
Ward, G. G.
Webb, G. R., M.B.E.
Willis, R. H.

### *Associate Members.*

Bates, W., O.B.E.
Bish, G. J.
Bradbury, R. H.
Clunas, J. F.
Dobson, J.
Emmott, H.
Gill, D.
Healy, L. T.
Jephson, R. P.
Kirk, M.
McAlonan, D.
McKee, F. J.
Martin, J.
Mitchell-Cocks, J.
Ogilvie, W.
Roberts, P. A.
Stobie, H. E.
Thomas, G. T.
Walter, L. H., M.A.

### *Graduates.*

Hollinrake, J. S.
Palmer, W. G.

### *Students.*

Ablett, L.
Ash, R. H. H.
Cox, W. L.
Davis, G. C. C.
Langley, H. W.

### *Associates.*

Barrett, A.
Hassard, Lt.-Col. H. S.
Parsons, The Hon. R. C.
Walmisley, A. T.

Of the foregoing, the Institution has suffered especially in the loss of the following distinguished members:—

Sir John Gavey, C.B. (Member of Council 1899–1900 and 1904, Vice-President 1901–1904, President 1905); Professor Gisbert Kapp (Member of Council 1886, 1889–1891, 1893–1896, Chairman of the Birmingham Local Section 1907, Vice-President 1907, President 1909); Professor Alexander Graham Bell (elected Member 1877 and Honorary Member 1913); Mr. Sidney Sharp (Member of Council 1890 and Honorary Auditor 1904–1918); Mr. H. Woodville Miller (Member of Council 1896–1898); Mr. M. H. Robinson (Member of Council 1901–1903); Mr. G. G. Ward (Local Honorary Secretary and Treasurer for the U.S.A. 1876–1922); and Prof. Sir James Dewar, M.A., F.R.S. (elected Member 1881).

## (10) Institution Building.

The Council are highly gratified at the continued use of the Institution theatre and rooms by a very large number of allied and kindred societies.

## (11) Meetings and Papers.

A statement of the total number of meetings and conferences held during the past twelve months and of papers read, lectures, etc., will be found in Appendixes B and C to this Report.

In this connection, the Council gladly refer again to the generous devotion by members of the Institution of their time and expert knowledge to the work of its various Committees.

The Premiums awarded by the Council for papers will be announced at the Annual General Meeting, or as soon as possible thereafter.

## (12) Ordinary Meetings.

The discussions have been consistently maintained at a high level, and have been more spontaneous than in the past. The Council wish to tender the best thanks of the Institution to the various speakers who place their knowledge and experience at the disposal of their fellow members by reading papers or taking part in the discussions.

As regards the attendances at the meetings, the fact that, owing to the many Centres and Sub-Centres of the Institution, the same paper is read at several places, appears to react unfavourably on the attendance at any particular meeting, a result which, in the case of highly technical papers, may need consideration in the future.

## (13) Local Centres and Sub-Centres.

In accordance with the Bye-Laws of the Chartered Institution, the former designation of "Territorial Centre" has been changed to "Local Centre."

The Reports of the various Centres show that the attendances at their meetings have been satisfactory.

During the Session the President paid visits to the Centres at Birmingham, Bristol, Dublin, Glasgow, Leeds, Manchester and Newcastle-upon-Tyne, and to the Sub-Centres at Liverpool, Loughborough, Middlesbrough and Sheffield.

On the 1st February, 1923, the Council granted a petition for the formation of a Centre at Liverpool, in place of the former Sub-Centre.

## (14) Technical Libraries for Local Centres.

The Council decided during the Session to supply technical books to the value of £50 to any Centre wishing to set up a Technical Library, provided that suitable accommodation is available, and that each collection is maintained and added to locally, the books remaining the property of the Institution.

## (15) Local Honorary Secretaries Abroad.

During the Session the Council appointed Mr. Gano Dunn, a Past-President of the American Institute of Electrical Engineers, to be Local Honorary Secretary for the United States of America, in place of the late Mr. G. G. Ward.

The Council also appointed Mr. M. L. Kristiansen, Chief Engineer of the Kristiania Government Telephone Service, to be Local Honorary Secretary for Norway.

## (16) Wireless Section.

The Wireless Section of the Institution has held eight meetings, at which nine papers were read.

## (17) Informal Meetings.

The Informal Meetings during the past Session have maintained their interest and, though the average attendance was below that of last year, the subjects selected have been keenly debated.

On the score of assisting in the training of speakers, the Informal Meetings have undoubtedly well served their purpose this Session, and a number of new speakers have contributed to the discussions.

The Annual Smoking Concert was greatly enjoyed by the large audience which attended, and the Benevolent Fund has benefited by the proceeds.

### (18) Students' Sections.

The number of Students on the Register of the Institution has reached a record total of 2 869, representing 26 per cent of the total membership.

A very full programme of meetings, visits to works, and social functions was carried out during the Session by the eight Students' Sections now in existence, viz. in London, Birmingham, Glasgow, Leeds, Liverpool, Manchester, Newcastle and Sheffield.

Addresses to the London Students' Section were given by the President and Mr. C. H. Wordingham, C.B.E., Past-President.

A Students' visit to Cardiff and district, organized by the London Students' Section, took place from the 24th to the 28th July, 1922. The following works were visited: The Melingriffith Tin Plate Works, Messrs. Vivian's Hafod Copper Works, Messrs. Baldwin's Landore Steel Works, The Britannia Colliery, The Barry Docks (G.W. Rly.), Messrs. Lewis and Mayer's Cement Works.

The Council have cordially thanked the firms named for the courtesy shown by them on the occasion, and for the facilities afforded, which very materially helped to make the visit an acknowledged success.

The Council have also thanked Mr. J. H. Reyner (Honorary Secretary, London Students' Section) for his valuable work in organizing the visit.

### (19) Scholarships.

The following Scholarships have been awarded by the Council:—

*David Hughes Scholarship.*

(Value £40; tenable for one year.)

W. H. M. Hellier (University College, Cardiff).

*Salomons Scholarship.*

(Value £50; tenable for one year.)

A. H. Maggs (Bristol University).

*Paul Scholarship.*

(Value £50; tenable for one year.)

C. A. Wilck (Finsbury Technical College).

*War Thanksgiving Education Research Fund* (*No.* 1).

A grant of £100 for educational purposes has been made this year by the Council under the provisions of the Trust Deed to R. H. Holmes (Armstrong College, Newcastle-upon-Tyne).

### (20) Conversazione.

The Annual Conversazione was held at the Natural History Museum, South Kensington, London, on the 29th June, 1922, when there was a record attendance of over 1 700 members and guests.

### (21) Annual Dinner.

The Annual Dinner was held at the Hotel Cecil, London, on the 6th February, 1923, the members and guests present numbering 480.

A message was received from H.R.H. The Prince of Wales regretting his inability to be present, and among the distinguished guests present were the following who spoke: The Rt. Hon. Neville Chamberlain (Postmaster-General), Sir W. Joynson-Hicks, Bart., M.P. (Parliamentary Secretary to the Overseas Department of the Board of Trade), and Sir Arthur Colefax, K.B.E., K.C.

An account will be found in the *Journal*, vol. 61, p. 400.

### (22) Summer Meeting.

The Summer Meeting in Scotland, admirably organized by the Committee of the Scottish Centre, took place from the 30th May to the 2nd June, 1922, and was very successful. A short account of the meeting will be found in the *Journal* (1922, vol. 60, Institution Notes, p. 26).

### (23) Portraits of Past-Presidents.

The Council have arranged for a complete set of enlarged photographs to be made of the Past-Presidents of the Institution. These, suitably framed, will be hung in the Institution's rooms as soon as the collection is complete.

### (24) Convention of American Institute of Electrical Engineers at Niagara.

At the above convention held at Niagara from the 26th to the 30th June, 1922, the Institution was represented by Mr. A. P. M. Fleming, C.B.E.

### (25) Associazione Elettrotecnica Italiana.

Signor Guido Semenza, the Institution's Local Honorary Secretary for Italy, represented the Institution at the celebration of the 25th Anniversary of the foundation of the Association last September.

### (26) Koninglijk Instituut Van Ingenieurs.

Similarly, the Institution was represented by Mr. P. V. Hunter, C.B.E., at the celebration of the 75th Anniversary of the foundation of the Royal Institute of Engineers at The Hague.

### (27) Library.

During the year 235 books and pamphlets have been presented to the Reference Library by members and others. A marked increase in attendance is recorded, the total number for the year being 2 526, of whom 125 were non-members, as against the previous highest yearly total of 1 651 in 1915–16.

The Council have pleasure in recording a continued increase in the circulation of books from the Lending Library. During the year 2 213 were issued to 814 borrowers, the corresponding numbers for the previous year being 1 450 and 564 respectively.

### (28) Museum.

After carefully considering the question of exhibiting the historical apparatus, particularly the larger apparatus and heavy machinery, the Council decided, in view of the limited space available in the Institution Building for this purpose, to offer to loan the collection, or such part of it as would be acceptable, to the Science Museum, South Kensington. The offer has been accepted and a considerable portion of the historical objects has now been transferred to the Science Museum.

By exhibiting the apparatus in a public Museum the Council feel that it will receive wider publicity, especially taking into consideration that a considerable number of the transferred objects would otherwise have had to remain stored in the basement of the Institution for an indefinite period.

In view of this arrangement the Council can in future accept apparatus only on the understanding that, on the recommendation of the Museum Committee, it may be transferred on loan to the Science Museum.

The following objects have been presented during the past year, and the Council desire to express their thanks to the donors :—

| *List of Apparatus.* | *Presented by* |
|---|---|
| Four examples of Navy telephones. | The Lords Commissioners of the Admiralty. |
| A collection of obsolete telegraph and telephone apparatus (14 objects). | The Engineer-in-Chief of the General Post Office. |
| A Holmes arc lamp dismantled from South Foreland Lighthouse. | The Elder Brethren of Trinity House. |
| An Ayrton-Perry magnifying spring voltmeter. | The Delegacy of the City and Guilds (Engineering) College. |
| An Ayrton-Perry magnifying spring ammeter. | The Delegacy of the City and Guilds (Engineering) College. |
| An Ayrton-Perry motor. | Professor T. Mather, F.R.S. |
| An Ayrton-Perry permanent magnet ammeter. | Professor T. Mather, F.R.S. |
| An Ayrton-Perry permanent magnet voltmeter. | Professor T. Mather, F.R.S. |
| A Serrin arc lamp. | The Committee of the Liverpool Public Libraries. |
| A Lorain contact-box. | C. Owen Silvers. |
| A collection of early telephone apparatus (21 objects). | F. G. C. Baldwin. |

### (29) Electrical Appointments Board.

During the past year there has been a gradual increase in the number of applicants for posts, the total being 130 as against 120 last year.

A classified Register of members seeking positions, containing particulars of their training and experience, is available for inspection at the Institution offices, and the Secretary of the Board will gladly put employers into touch with highly qualified electrical engineers in practically all branches of the profession.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the Register.

Vacancies may also be reported to the Honorary Secretaries of Local Centres and Sub-Centres, who will at once report such vacancies to the Secretary of the Board at the Institution offices.

### (30) The Journal of the Institution.

The number of pages in the 1922 Volume was 1 002 (excluding 18 plates of half-tone illustrations), as compared with 852 pages in 1921. The large increase in the number of pages was due to the Special Number of the *Journal* containing an account of the proceedings at the Commemoration Meetings held in February, 1922.

The net cost of printing and publishing the *Journal* in 1922, after allowing for sales, was £4 604, as compared with £4 936 in 1921. This reduction is all the more gratifying when the large increase in the number of copies and the amount of matter printed is taken into account.

### (31) Advertisements in the Journal.

The Council's intention of publishing in the *Journal* a Classified Index of British Manufacturers, which was referred to in the last Report, could not for a number of reasons be proceeded with, but in reconsidering the position the Council felt that it was in the best interests of the Institution to revert to the practice which obtained until 1913 of publishing advertisements in the *Journal.* A beginning was accordingly made with the March number, and the *Journal* will in future contain advertisements.

### (32) "Science Abstracts."

The Council deeply regret to have to record the death in September last of Mr. L. H. Walter, M.A., who had been Editor of *Science Abstracts* since 1903. In his place, the Council have appointed Mr. W. R. Cooper, M.A., B.Sc., to be the Editor of the publication.

The Physics volume of *Science Abstracts* for 1922 contained 104 more pages than that for 1921, and the Electrical Engineering volume, 8 more pages.

The contribution of the Institution towards the cost of publishing *Science Abstracts* in 1922 was £1 085, as compared with £978 in 1921. This increase was not expected in the earlier part of the year, but was rendered necessary by the large amount of belated material which came from the Continent after the War. The position is now becoming more normal in this respect. The Committee of Management have also taken steps to increase the revenue of *Science Abstracts* so that the burden falling on the Institution should be materially less in the future.

### (33) Wiring Rules.

Owing to the many divergencies of view and the large number of amendments made to the Preliminary Draft, it has been impossible to complete the revision of the Rules during the Session under review. It is hoped that the Committee will be able to report finally on this matter at an early date.

### (34) Model Conditions for Contracts.

The Council have appointed a Committee to prepare Model Conditions of Contract for :—

(*a*) "Home" orders when no erection is included in the contract;

(*b*) "Export" orders, with or without erection.

The above are still under consideration by the Committee and, it is hoped, will shortly be published.

### (35) British Electrical Proving House.

The Committee appointed by the Council to report on the question of setting up a National Proving House for the testing of electrical goods and materials have not yet completed their Report. Some progress has been made with the preparation of a scheme for the purpose, and other bodies interested in the matter have been consulted.

### (36) Voluntary Registration of Electrical Contractors.

A scheme to give effect to the above has been prepared by the Committee appointed for the purpose and has been approved by the Council. The scheme provides for a Registration Authority consisting of nominees of the Institution and of interested bodies which will carry out as a separate body the registration of Electrical Wiring Contractors.

### (37) Electricity Regulations.

The Regulations Sub-Committee of the Power Lines Committee has been given the status of a Committee under the name of the Electricity (Supply) Regulations Committee, and as a consequence the original Power Lines Committee, together with its two Sub-Committees (Wayleaves and Factors of Safety), has been dissolved. A set of draft Regulations for Low and Medium Pressure Overhead Lines prepared by the Committee was circulated to the Associations concerned and, after revision, was, together with a set of draft Regulations for High Pressure Lines, submitted on behalf of the Council to the Electricity Commissioners for their approval.

The Committee are now considering amendments to the Board of Trade Regulations, (*a*) for securing the safety of the Public, and (*b*) for ensuring a proper and sufficient supply of Electrical Energy, for the purpose of enabling the Council to submit a Report thereon to the Electricity Commissioners.

### (38) Committee on Electricity in Agriculture.

The Council have appointed a Committee as above, with the following terms of reference :—

To consider and report to the Council on the following points :—

(*a*) Whether there are any special features in connection with the supply and use of electricity in agriculture which need special attention from the Institution by way of education or propaganda, and, if so, what action the Committee recommend the Council to take;

(*b*) And for the purpose of making a recommendation :—

- (i) To investigate and report upon the actual or probable load factors and annual consumption of farms in this country and elsewhere, and on the capital cost to Supply Authorities of supply to farms, and to farmers of the machinery for utilizing the supply, and of the economic results likely to be obtained by Supply Authorities and farmers;
- (ii) To report on the desirability of a permanent Sectional Committee of the Institution for dealing with this question.

### (39) Irish Free State.

As the result of representations made by the Committee of the Irish Centre, the Council have authorized that Committee to appoint, on behalf of the Irish Free State Government, a Committee to advise, if requested, the Irish Government on matters concerning Electrical Engineering. This Advisory Committee has been appointed.

### (40) British Manufactured Goods.

During the year under review the Council were in communication with the National Federation of Iron and Steel Manufacturers, and the following Resolution was passed by the Council at a meeting held on the 1st February, 1923 :—

> "In view of the present state of trade and employment, the Council request members who place, or who advise upon the placing of orders, to specify as far as practicable that the plant and material ordered shall be of British manufacture."

Similarly, the Federation has agreed to recommend its members as far as possible to place orders for electrical material with British firms for British material.

### (41) Electrical Engineering Training in Technical Schools.

The scheme for the issue of certificates and diplomas to students who are trained and pass certain examinations under conditions approved by the Board of Education and the Institution, which was approved by the Council last Session, has since been approved by the Board. The Joint Committee of representatives of the Board of Education and the Institution provided for under the scheme has been set up and certain courses of training and examination syllabuses and schools have been approved. It is expected that the scheme will come into operation for the educational session of 1923–24.

### (42) Engineering Joint Council.

As the result of a conference summoned by the Institution of Civil Engineers, which was attended by representatives of that Institution, and of the Institutions of Electrical Engineers, Mechanical Engineers, and Naval Architects, an Engineering Joint

Council has been set up, the constitution of which is still under consideration and is provisionally as follows :—

1. A Council to be entitled "The Engineering Joint Council" shall be formed. It shall consist of two members of the Council of each of the following Institutions in the first instance, appointed from time to time by their Councils severally :—

The Institution of Civil Engineers,
The Institution of Mechanical Engineers,
The Institution of Naval Architects,
The Institution of Electrical Engineers,

which shall be called the Founder Institutions.

2. The Members of the Joint Council shall be appointed annually, and shall be eligible to serve for not more than four years consecutively. One of the first two appointed by each Institution shall serve for not more than two years, but shall be eligible for reappointment for a further period of not more than four years consecutively.

3. The Chairman shall be elected annually by the Joint Council, and the Secretary of the Institution represented by the Chairman for the year shall act as Secretary of the Joint Council. The Chairman shall be chosen from the several Institutions in rotation.

4. The Joint Council shall consider matters referred to it by the Council of any one of the constituent Institutions. It shall not initiate proposals affecting the Institutions, and shall be an advisory body without executive powers. Provision is also made in the draft Bye-Laws for the admission of other Institutions or Societies to representation on the Joint Council, subject to certain conditions.

### (43) Electrical Research Association.

The Electrical Research Association has made good progress on all the researches in hand. A comprehensive Report on the heating of buried cables has been published by the Institution, which should lead to the saving of very large sums by Electric Supply Authorities. The work on insulating oils has resulted in the forthcoming issue of a British Standard Specification.

The researches on electric control apparatus are establishing new criteria of design. The work on overhead line materials has furnished new data which have been placed at the disposal of the Institution. A general levelling up of insulating materials of all kinds is being effected, and attention is being directed to the development of new materials with improved characteristics. Researches for the improvement of steam turbines and condensers have been extended.

The Institution has increased its annual subscription from £200 to £300, a corresponding grant being obtained from the Department of Scientific and Industrial Research.

Members are invited to communicate with the Director of the Association at 19, Tothill-street, Westminster, S.W.1, on the work of the Association and all matters relating to co-operative research.

### (44) The British Engineering Standards Association.

Progress in connection with the Standardization of Electrical Materials and Apparatus has been steady during the past year and the following British Standard Specifications were issued :—

B.S.S. No. 7. Insulated Annealed Copper Conductors for Electric Power and Light.
B.S.S. No. 96. Parallel-Sided Carbon Brushes.
B.S.S. No. 109. Air-Break Knife and Laminated Brush Switches.
B.S.S. No. 1110. Air-Break Circuit Breakers.
B.S.S. No. 152. Metric Dimensions of Insulated Annealed Copper Conductors for Electric Power and Light.
B.S.S. No. 156. Enamelled Plain Copper Wires.
B.S.S. No. 168. Electrical Performance of Industrial Electric Motors and Generators (in place of No. 72 withdrawn).
B.S.S. No. 174–184. Overhead Line Wire Material for Telegraph and Telephone purposes.

The Specification for Insulating Oils for use in Transformers, Circuit Breakers, etc., has been approved and is in the printers' hands.

Progress has also been made in the preparation of the list of terms and definitions for use in Electrical Engineering. This list, which is an extension of that prepared by the Institution some few years ago, now comprises some 1 200 terms and, it is hoped, will be published shortly.

### (45) The International Electrotechnical Commission.

Meetings of the Advisory Committees on Rating of Electrical Machinery, Symbols, Standard Pressures for Distribution and Insulators and Screw Lamp Caps and Holders were held in Geneva last November and good progress has been made in the various subjects under review. Of the representatives of the Institution on the British National Committee of this Commission Colonel R. E. Crompton, C.B., and Mr. Roger T. Smith attended the meetings.

### (46) Benevolent Fund.

The Committee of Management of the Benevolent Fund of the Institution report that on the 31st December, 1922, the Capital Account of the Fund stood at £9 969 11s. 3d., and the accumulated income at £1 463 1s. 3d. The donations and subscriptions to the Fund in 1921 amounted to £2 399 13s. 4d.

In the course of the year 40 grants were made to 16 persons, amounting to a total of £776 5s. 0d.

With a view to increasing the subscriptions to the Fund, the Committee have appointed a Local Honorary Treasurer of the Fund for each Local Centre of the Institution and also for the Sheffield Sub-Centre.

### (47) Annual Accounts.

The Annual Accounts for the year 1922 will be found on pages 604 to 609 of No. 318 of the *Journal.*

*Excess of Income over Expenditure.*—After making provision for contingencies as in the previous year, there is a margin to the good on the Revenue Account for 1922 of £862 2s. 8d. This amount, which has been carried to the credit of the General Fund, compares with £639 2s. 10d. in 1921, an increase of £222 19s. 10d.

*Mortgages.*—

| | £ | s. | d. |
|---|---|---|---|
| In the Accounts for 1921 these stood at | 24 331 | 19 | 11 |
| Amount of repayments during the year | 3 993 | 13 | 6 |
| They now stand at .. .. .. | 20 338 | 6 | 5 |

*Life Compositions Fund.*—The total of the Fund on the 1st January, 1921, was £5 590 10s. 0d., and an amount of £94 8s. 3d. was received for Life Compositions during the year. There being no obligation under the Bye-Laws of the Chartered Institution to keep these in a separate fund, the whole of these amounts has been transferred to the General Fund.

*Assets.*—Taking the Tothill Street property and the investments at cost, and the Institution Building and lease, the library and furniture, etc., at the values standing in the books after writing off depreciation—

| | £ | s. | d. |
|---|---|---|---|
| the Assets amount to .. .. .. | 120 430 | 1 | 2 |
| against Liabilities .. ... .. | 6 030 | 19 | 1 |
| leaving a surplus of .. .. .. | £114 399 | 2 | 1 |
| which, in comparison with that of the year 1921, viz. .. .. .. | 108 939 | 7 | 11 |
| shows an improvement of .. .. | £5 459 | 14 | 2 |

The balance of £114 399 2s. 1d. is made up as follows :—

| | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|
| *Assets.* | | | | | | |
| *Properties.* | | | | | | |
| Institution Building and Tothill Street Property .. .. | 92 289 | 3 | 11 | | | |
| Less Mortgages .. | 20 338 | 6 | 5 | | | |
| | | | | 71 950 | 17 | 6 |
| Investments, Cash, etc. | | | | 41 886 | 18 | 9 |
| Stock of Paper, Libraries and Furniture .. | | | | 6 592 | 4 | 11 |
| | | | | £120 430 | 1 | 2 |
| Less *Liabilities.* | | | | | | |
| Trust Fund Income Accounts .. .. | 360 | 19 | 4 | | | |
| Sundry Creditors .. | 4 062 | 3 | 2 | | | |
| Repairs Suspense Account .. .. | 1 261 | 5 | 1 | | | |
| Subscriptions received in advance .. .. | 346 | 11 | 6 | | | |
| | | | | 6 030 | 19 | 1 |
| | | | | £114 399 | 2 | 1 |

### (48) THE INSTITUTION AND BODIES ON WHICH IT IS REPRESENTED.

For convenience of reference, there is attached hereto (Appendix D) a diagram showing the organization of the Institution and its representation on other bodies.

## APPENDIX A.

### MEMBERSHIP OF THE INSTITUTION.

The changes in the membership since the 1st April, 1922, are shown in the following table :—

| | Hon. Mem. | Mem. | Assoc. Mem. | Grad. | Studt. | Assoc. | Total. | TOTAL. |
|---|---|---|---|---|---|---|---|---|
| Totals at 1 April, 1922 | 10 | 1 800 | 4 661 | 934 | 2 455 | 415 | | 10 275 |
| Additions during the year :— | | | | | | | | |
| Elected | .. | 16 | 157 | 144 | 692 | 9 | 1 018 | |
| Reinstated | .. | 5 | 4 | 1 | 18 | .. | 28 | |
| Transferred to | 1 | 68 | 87 | 79 | .. | .. | 235 | |
| Total | 1 | 89 | 248 | 224 | 710 | 9 | 1 281 | |
| Deductions during the year :— | | | | | | | | |
| Deceased | 1 | 17 | 19 | 2 | 5 | 4 | 48 | |
| Resigned | .. | 16 | 33 | 16 | 55 | 9 | 129 | |
| Lapsed | .. | 6 | 60 | 41 | 122 | 4 | 233 | |
| Transferred from | .. | 1 | 62 | 43 | 114 | 15 | 235 | |
| Total | 1 | 40 | 174 | 102 | 296 | 32 | 645 | |
| Net Increase | | .. | .. | .. | .. | .. | .. | 636 |
| Totals at 1 April, 1923 | 10 | 1 849 | 4 735 | 1 056 | 2 869 | 392 | | 10 911 |

## APPENDIX B.

### MEETINGS.

The following is a list of the meetings held during the past twelve months :—

| | |
|---|---|
| Ordinary Meetings .. | 17 |
| Wireless Sectional Meetings .. .. .. | 8 |
| Informal Meetings .. | 8 |
| Council Meetings .. | 19 |
| Local Centres :— | |
| Irish .. .. .. | 9 |
| Mersey and North Wales (Liverpool) .. | 10 |
| North-Eastern .. | 11 |
| North Midland .. | 12 |
| North-Western .. | 13 |
| Scottish .. .. | 10 |
| South Midland .. | 11 |
| Western .. .. | 10 |
| Local Sub-Centres :— | |
| Dundee .. .. | 6 |
| East Midland .. | 10 |
| Sheffield .. .. | 6 |
| Tees-side .. .. | 8 |
| Students' Sections :— | |
| London .. .. | 9 |
| Birmingham .. .. | 11 |
| Leeds .. .. .. | 6 |
| Liverpool .. .. | 10 |
| Manchester .. .. | 8 |
| Newcastle .. .. | 15 |
| Scottish .. .. | 6 |
| Sheffield .. .. | 11 |
| Committees :— | |
| Benevolent Fund .. | 9 |
| Electricity (Supply) Regulations .. | 26 |
| Examinations .. | 7 |
| Finance .. .. | 13 |
| General Purposes .. | 8 |
| Informal Meetings .. | 8 |
| Local Centres .. | 2 |
| Membership .. .. | 7 |
| Model General Conditions (and Sub-Committee) .. | 6 |
| Papers (and Sub-Committee) .. | 8 |
| Proving House Sub-Committee .. .. | 1 |
| Registration of Electrical Contractors .. | 3 |
| "Science Abstracts" | 6 |
| War Memorial .. | 2 |
| Wireless Section .. | 5 |
| Wiring Rules .. | 8 |
| Other Committees .. | 6 |
| Total .. | 369 |

## APPENDIX C.

### Addresses.

| *Author.* | *Title.* |
|---|---|
| R. D. Archibald, Member. | Chairman's Address (Dundee Sub-Centre). |
| F G. C. Baldwin, Member. | Chairman's Address (North-Eastern Centre). |
| A. S. Barnard, Member. | Chairman's Address (North-Western Centre). |
| Prof. W. Cramp, D.Sc., Member. | Chairman's Address (South Midland Centre). |
| F. Gill, President. | Inaugural Address. |
| F. Gill, President. | Address to the London Students' Section. |
| A. S. Hampton, Member. | Chairman's Address (Scottish Centre). |
| E. C. Handcock, Member | Chairman's Address (Irish Centre). |
| J. S. Highfield, Past-President. | Address to the Western Centre. |
| J. F. Nielson, Member. | Address to the Scottish Students' Section. |
| W. Pearson, Associate Member. | Chairman's Address (East Midland Sub-Centre). |
| W.P. Richmond, Associate Member. | Chairman's Address (Tees-side Sub-Centre). |
| F. Tremain, Member. | Chairman's Address (Western Centre). |
| B. Welbourn, Member. | Chairman's Address (Liverpool Sub-Centre). |
| H. West, Associate Member. | Chairman's Address (Sheffield Sub-Centre). |
| W. B. Woodhouse, Member. | Chairman's Address (North Midland Centre). |
| C. H. Wordingham, C.B.E., Past-President. | Address to the London Students' Section. |

### Lectures, Etc.

| | |
|---|---|
| E. E. Brooks, Associate Member. | Exhibition of Lantern Slides illustrating Lines of Electric Force. |
| F. Creedy, Associate Member. | "Variable-Speed Alternating-Current Motors without Commutators." |
| Prof. M. Maclean, D.Sc., LL.D., F.R.S.E., Member. | "Hydro-Electric Resources of the Scottish Highlands." |
| R. B. Mitchell, Member. | "The Dalmarnock Power Station." |
| Dr. H. W. Nichols. | "Transoceanic Wireless Telephony." |
| Sir E. Rutherford, F.R.S. | "Electricity and Matter" (The Thirteenth Kelvin Lecture). |
| A. G. Warren, Member. | "The X-Ray Examination of Materials." |
| B. Welbourn, Member. | Exhibition of cinematograph films on "The Electrification of the Chicago, Milwaukee and St. Paul Railroad." |

### Papers read at Meetings and Accepted for Publication in the Journal.

| | |
|---|---|
| J. W. Beauchamp, Member. | "Co-operation between the Architect and the Electrical Engineer." |
| J. Caldwell, Member. | "Electric Arc Welding Apparatus and Equipment." |

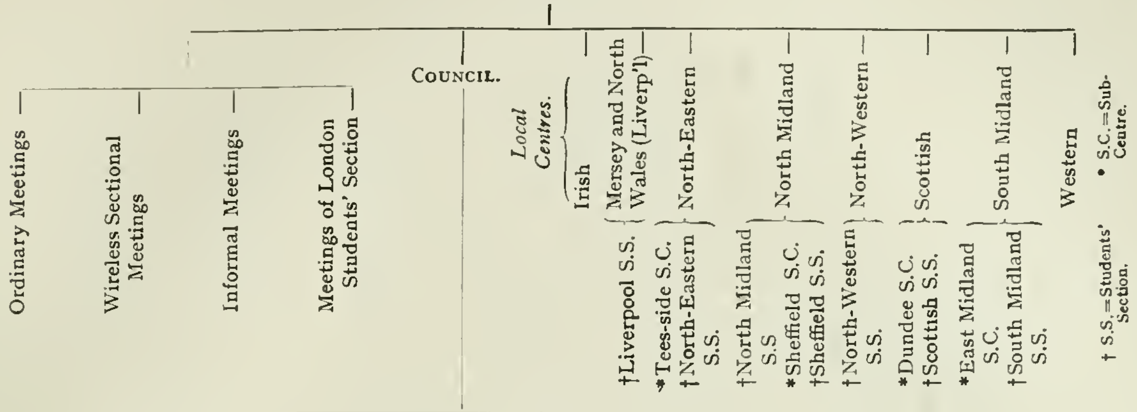
### Papers read at Meetings and Accepted for Publication in the Journal—*continued.*

| *Author.* | *Title.* |
|---|---|
| C. F. Elwell, Member. | "The Design of Radio Towers and Masts: Wind-Pressure Assumptions." |
| C. S. Franklin. | "Short-Wave Directional Wireless Telegraphy." |
| W. A. Gillott, Associate Member. | "Domestic Load Building: a few suggestions upon Propaganda Work." |
| J. Hollingworth, M.A., B.Sc., Associate Member. | "The Measurement of the Electric Intensity of Received Radio Signals." |
| Francis Hooper, F.R.I.B.A. | "Co-operation between the Architect and the Electrical Engineer." |
| Prof. C. F. Jenkins, C.B.E., M.A. Member. | "A Dynamic Model of Tuned Electrical Circuits." |
| Dr. G. Kapp (the late), Past-President. | "The Improvement of Power Factor." |
| N. Lea, B.Sc., Associate Member. | "The Performance of a Radio-Telegraphic Transmitter, with special reference to the New Installation at North Foreland." |
| Dr. N. W. McLachlan, Member | "Magnetic Drum High-Speed Recorder and Key Transmitter." |
| S. W. Melsom, Associate Member, and E. Fawssett, Member. | "Permissible Current Loading of British Standard Impregnated Paper - Insulated Electric Cables" (Report of the British Electrical Research Association). |
| H. Morris-Airey, C.B.E. | "Development of Naval High-Power Valves." |
| E. B. Moullin, M.A., Associate Member. | "A Direct-reading Thermionic Voltmeter and its Applications." |
| G. H. Nelson, Member. | "Works Production." |
| Dr. S. S. Richardson. | "An Oscillograph Investigation of the Gulstad Relay." |
| P. J. Robinson, Member. | "The Maintenance of Voltage on a D.C. Distribution System by means of a Fully Automatic Substation." |
| J. Rosen, Member. | "Some Problems in High-Speed Alternators, and their Solution." |
| R. L. Smith-Rose, M.Sc., Associate Member, and R. H. Barfield, B.Sc., Student. | "The Effect of Local Conditions on Radio Direction-Finding Installations." |
| A. M. Taylor, Member. | "The Possibilities of Transmission by Underground Cables at 100 000/150 000 Volts." |

In addition, a number of papers have been accepted for publication in the *Journal* without being read at meetings.

## APPENDIX D.

## THE INSTITUTION OF ELECTRICAL ENGINEERS.



### COMMITTEES.
(*Standing.*)

Benevolent Fund
Electrical Appointments Board
Examinations
Finance
General Purposes
Informal Meetings
Library
Local Centres
Membership
Papers
Paul Scholarship
" Science Abstracts "
Ship Electrical Equipment
Technical Co-operation
Wireless
Wiring Rules

*Sectional Committees.*
- Electricity in Mines
- Electro-Chemistry and Electro-Metallurgy
- Lighting and Power
- Telegraphs and Telephones
- Traction

### COMMITTEES.
(*Special.*)

Electricity in Agriculture
Electricity (Supply) Regulations
Model General Conditions
Patent Law
Proving House
Registration of Electrical Contractors
Technical Education
War Memorial

### BODIES ON WHICH THE INSTITUTION IS REPRESENTED.

Air Conference, 1923
Air Conference, International, 1923
Birmingham Chamber of Commerce
Bradford Public Libraries Committee
Bristol University
British Electrical and Allied Industries Research Association
British Empire Exhibition, 1924
British Engineering Standards Association
British National Committee of the International Electrotechnical Commission
British National Illumination Committee of the International Illumination Commission
Corrosion Committee of Institute of Metals
Darlington Board of Invention and Research
Electrical Development Association
Engineering Joint Council
Fourth International Road Congress
Fuel Economy Committee of British Association
Imperial College of Science and Technology, Governing Body
Imperial Mineral Resources Bureau Conference
Institution of Civil Engineers, Engine and Boiler Testing Committee
Institution of Heating and Ventilating Engineers, Utilization of Exhaust Steam and Waste Heat Committee
International Navigation Congress, 1923
International Scientific Unions
International Testing Association
Joint Education Committee for National Certificates in Electrical Engineering
Leeds Civic Society
Leeds Municipal Technical Library Committee
Loughborough Technical College Advisory Committee
Metalliferous Mining (Cornwall) School, Governing Body
Middlesbrough Technical College
Mines Department, Electrical Storage Battery Locomotive Committee
National Committee for Physics (Royal Society)
National Committee in Radio Telegraphy (Royal Society)
National Physical Laboratory, General Board
Newcastle-upon-Tyne Chamber of Commerce
Paris Conference on E.H.T. Lines (Union des Syndicats de l'Electricité)
Professional Classes Aid Council

(*Continued at foot of col.* 1.)

(*Continued from foot of col.* 3.)

Radiographers, Society of
Röntgen Society Advisory Committee for British X-Ray Industry
Royal Engineer Board
Scientific and Industrial Research Advisory Council, Engineering Committee
Transport, Ministry of, Advisory Panel
War Office Committee on Engineer Organization
Women's Engineering Society

# THE INSTITUTION OF ELECTRICAL ENGINEERS.

## REVENUE ACCOUNT FOR THE YEAR ENDED 31ST DECEMBER, 1922.

**Dr.** EXPENDITURE.

| Year ended 31 Dec., 1921.* £ s. d. | | £ s. d. | £ s. d. |
|---|---|---|---|
| | To **Management** :— | | |
| | Salaries and Wages (including Staff Provident Scheme and War Bonus) ... | 10,119 2 1 | |
| | National Insurance ... ... ... ... | 63 12 3 | |
| | Accountants' Fees ... ... ... ... | 52 10 0 | |
| | Printing ... ... ... ... ... | 973 14 1 | |
| | Stationery and Office Requisites ... ... | 463 1 6 | |
| | Addressing ... ... ... ... ... | 33 15 10 | |
| | Postage of Correspondence and Notices | 700 19 1 | |
| | Telephone ... ... ... ... ... | 65 7 6 | |
| | Travelling Expenses ... ... ... | 79 12 3 | |
| | Bank Charges ... ... ... ... | 20 11 11 | |
| 11,392 6 2 | | | 12,578 6 6 |
| | ,, **Institution Building** :— | | |
| | Ground Rent ... ... ... ... | 2,201 0 0 | |
| | Rates and Taxes ... ... ... ... | 2,785 19 11 | |
| | Heating ... ... ... ... ... | 423 14 6 | |
| | Lighting and Power ... ... ... | 265 11 10 | |
| | Insurance ... ... ... ... ... | 154 6 8 | |
| | Reserve for Repairs ... ... ... | 600 0 0 | |
| | Estate Agents' Fees ... ... ... | 78 15 0 | |
| | Household Requisites and Cleaning ... | 181 19 1 | |
| | Final Settlement with H.M. Office of Works | 222 7 11 | |
| 5,595 11 1 | | 6,913 14 11 | |
| 4,866 8 0 | *Less* Rents from Tenants ... ... ... | 2,491 8 0 | |
| | | | 4,422 6 11 |
| 1,243 6 0 | ,, **Interest on Mortgages** ... ... ... ... ... | | 990 12 10 |
| 160 6 5 | ,, **Furniture and Fittings** (Repairs and Renewals and Valuers' Fees) ... ... ... | | 170 0 11 |
| | ,, **Journal** :— | | |
| | Printing ... ... ... ... ... | 4,213 13 1 | |
| | Postage ... ... ... ... ... | 1,331 13 3 | |
| | Wrappers and Envelopes ... ... ... | 221 2 10 | |
| | | 5,766 9 2 | |
| | *Less* Sales ... ... ... ... | 1,162 5 10 | |
| 4,936 0 5 | | | 4,604 3 4 |
| 96 18 5 | ,, **Lending Library** (Books, Printing, Postage, etc.) ... | | 81 2 4 |
| | ,, **Thompson Memorial Library** :— | | |
| 5 2 0 | Insurance, Valuers' Fees, etc. ... ... ... ... ... | | 32 8 0 |
| 308 18 8 | ,, **Expenses in Connection with Royal Charter and Winding up of Old Institution** ... ... ... | | 420 19 1 |
| | ,, **Science Abstracts** :— | | |
| | Salaries, Abstracting, Printing, Postage, etc.... ... ... ... ... ... | 4,080 8 11 | |
| | *Less* Subscriptions, Sales, and Advertisements ... ... ... ... ... | 2,995 14 0 | |
| 978 8 7 | | | 1,084 14 11 |
| | Carried Forward ... ... ... | | £24,384 14 10 |

INCOME. **Cr.**

| Year ended 31 Dec., 1921.* £ s. d. | | £ s. d. | £ s. d. |
|---|---|---|---|
| 28,361 1 4 | By **Subscriptions** ... ... ... ... ... ... ... | | 31,197 10 9 |
| 1,826 17 0 | ,, **Entrance Fees and Vellum Diploma Fees** ... ... ... ... ... ... ... | | 1,265 5 0 |
| —— | ,, **Life Compositions** ... ... ... ... ... ... | | 94 8 3 |
| 1,985 8 4 | ,, **Dividends and Interest** ... ... ... ... ... | | 1,910 11 10 |
| 114 0 8 | ,, **Model General Conditions** ... ... ... ... | | 201 16 8 |
| —— | ,, **Wiring Rules** ... ... ... ... ... ... ... | | 11 17 6 |
| 7 4 2 | ,, **Ship Wiring Rules** ... ... ... ... ... ... | | 6 10 0 |
| | ,, **Tothill Street Property** :— | | |
| | Rents from Tenants ... ... ... ... | 1,277 8 8 | |
| | *Less* Ground Rent, Repairs, Alterations, Rates, Taxes, etc. ... ... ... | 439 19 3 | |
| 510 3 11 | | | 837 9 5 |
| —— | ,, **Examinations** (Fees, etc., less Expenses) ... ... ... | | 133 11 1 |
| 32,812 16 5 | Carried Forward ... ... ... ... | | £35,659 0 6 |

## REVENUE ACCOUNT—*continued.*

**Dr.** EXPENDITURE—*continued.*

| | | £ s. d. | £ s. d. |
|---|---|---|---|
| | Brought Forward ... ... ... ... | ... | ... 24,384 14 10 |
| | To Institution Meetings :— | | |
| | Advance Proofs ... ... ... ... | 146 8 10 | |
| | Reporting ... ... ... ... ... | 126 10 6 | |
| | Grant to London Students' Section ... | 30 4 10 | |
| | Honorarium to Kelvin Lecturer ... ... | 25 0 0 | |
| | Refreshments, Assistance, etc. ... ... | 263 3 5 | |
| | Travelling Expenses of Authors of Papers ... ... ... ... ... | 34 11 10 | |
| | Commemoration Meetings ... ... | 220 1 1 | |
| | Unveiling and Dedication of War Memorial ... ... ... ... | 85 6 6 | |
| *674 5 1* | | | 931 7 9 |
| | ,, Local Centres :— | | |
| | Money Grants (including Travelling Expenses of Authors of Papers) ... | 2,055 14 3 | |
| | Travelling Expenses ... ... ... | 631 18 2 | |
| | Books for Leeds Joint Engineering Library | 47 10 0 | |
| *2,371 7 5* | | | 2,735 2 5 |
| *208 10 2* | ,, Premiums for Papers ... ... ... | ... ... | 212 13 5 |
| — | ,, Faraday Medal (Dies, Artist's Fees, etc.) | ... ... | 113 10 2 |
| | ,, Special Grants :— | | |
| | International Electrotechnical Commission ... ... ... ... ... | 150 0 0 | |
| | Electrical Research Association... ... | 200 0 0 | |
| | National Illumination Committee ... | 40 0 0 | |
| | Conjoint Board of Scientific Societies ... | 20 0 0 | |
| | Attendance of Delegate at Convention of American Institute of Electrical Engineers at Niagara ... ... ... | 50 0 0 | |
| *517 19 11* | | | 460 0 0 |
| *124 16 6* | ,, Annual Dinner ... ... ... ... | ... ... | 82 10 9 |
| *560 10 0* | ,, Conversazione... ... ... ... | ... ... | 500 4 2 |
| *15 10 10* | ,, Legal Expenses ... ... ... ... | ... ... | 94 17 6 |
| *97 11 8* | ,, Miscellaneous Expenses ... ... ... | ... ... | 78 6 2 |
| *25,055 6 9* | | | 29,593 7 2 |
| | ,, Amounts Transferred to :— | | |
| *277 12 2* | Sinking Fund (Premiums for Redemption of Cost of Building and Lease) ... | 277 12 2 | |
| *4,000 0 0* | Reserve Fund (Contingencies and Mortgage Redemption) ... ... | 3,000 0 0 | |
| | General Fund :— | | |
| — | Life Compositions received in 1922 ... | 94 8 3 | |
| *952 15 1* | Obligatory Repayment to Economic Life Assurance Society ... ... | 993 13 6 | |
| | Expenditure on— | | |
| *111 16 9* | Books and Binding for Library ... | 119 13 4 | |
| *1,776 2 10* | Furniture, Fittings and Apparatus | 718 3 5 | |
| *639 2 10* | **Balance carried to General Fund** ... | 862 2 8 | |
| | | | 6.065 13 4 |
| | | | £35,650 0 6 |

INCOME—*continued.* **Cr.**

| | £ s. d. |
|---|---|
| Brought Forward ... ... ... ... ... ... | 35,659 0 6 |
| | £35,659 0 6 |

---

[*] These columns do not add up to the respective totals of Income and Expenditure, as some of the items in the Accounts for 1921 did not occur in 1922.

# BALANCE SHEET, 31ST DECEMBER, 1922.

**Dr** LIABILITIES

| | | £ s. d. | £ s. d. |
|---|---|---|---|
| To ECONOMIC LIFE ASSURANCE SOCIETY :— | | | |
| On Mortgage of Institution Building (1909) ... | | 26,000 0 0 | |
| Since repaid ... ... ... ... ... | | 10,161 13 7 | |
| | | 15,838 6 5 | |
| On Mortgage of Tothill Street Buildings and Site (1910) ... ... ... | £11,500 0 0 | | |
| Since repaid ... ... ... | 7,000 0 0 | | |
| | | 4,500 0 0 | |
| | | | 20,338 6 5 |
| „ KELVIN LECTURE FUND :— | | | |
| As per last Balance Sheet ... ... ... ... ... ... | | | 648 13 0 |
| „ UNINVESTED BALANCES OF TRUST FUNDS ... ... ... ... | | | 360 19 4 |
| „ SUNDRY CREDITORS ... ... ... ... ... ... ... | | | 4,062 3 2 |
| „ SUBSCRIPTIONS RECEIVED IN ADVANCE ... ... ... ... | | | 346 11 6 |
| „ REPAIRS SUSPENSE ACCOUNT :— | | | |
| Balance (as per last Balance Sheet) ... ... | | 19 4 11 | |
| Amount set aside in 1922 ... ... ... ... ... | | 600 0 0 | |
| Payment from London County Council for dilapidations ... ... ... ... ... | | 1,100 0 0 | |
| | | 1,719 4 11 | |
| *Less* Expenditure on Repairs in 1922... ... | | 457 19 10 | |
| | | | 1,261 5 1 |
| „ RESERVE FUND (Contingencies and Mortgage Redemption) :— | | | |
| Balance at 1st January, 1922 ... ... ... | | 14,000 0 0 | |
| Amount transferred to Reserve Fund in 1922 ... | | 3,000 0 0 | |
| | | 17,000 0 0 | |
| *Less* Voluntary Instalment repaid to Economic Life Assurance Society on mortgage of Tothill Street Buildings and Site ... ... ... | | 3,000 0 0 | |
| | | | 14,000 0 0 |
| Carried Forward ... ... ... ... ... | | | 41,017 18 6 |

ASSETS. **Cr.**

| | £ s. d. | £ s. d. |
|---|---|---|
| By INSTITUTION BUILDING AND LEASE :— | | |
| Cost ... ... ... ... ... ... ... | 73,028 6 10 | |
| *Less* Reserve for Depreciation, being Surrender Values of Sinking Fund Policies ... ... | 4,015 14 8 | |
| | | 69,012 12 2 |
| „ SINKING FUND (Surrender Values of Policies for Redemption of Cost of Building and Lease) ... ... ... | | 4,015 14 8 |
| „ TOTHILL STREET BUILDINGS AND SITE (at cost) ... ... ... | | 19,260 17 1 |
| „ KELVIN LECTURE FUND INVESTMENT (at cost)* :— | | |
| £694 16s. 9d. 5 % War Stock ... ... ... ... ... | | 648 13 0 |
| „ LIBRARY (exclusive of the Ronalds Library and Faraday Papers, which are held in trust) :— | | |
| As per last Balance Sheet ... ... ... ... | 1,046 14 1 | |
| Additions in 1922 ... ... ... ... ... | 119 13 4 | |
| | 1,166 7 5 | |
| *Less* Depreciation (10 %) ... ... ... ... | 116 12 9 | |
| | | 1,049 14 8 |
| „ THOMPSON MEMORIAL LIBRARY (Contribution towards purchase) ... ... ... ... ... ... ... ... | | 1,000 0 0 |
| „ FURNITURE, FITTINGS, AND APPARATUS :— | | |
| As per last Balance Sheet ... ... ... ... | 3,516 2 2 | |
| Expenditure in 1922 ... ... ... ... ... | 718 3 5 | |
| | 4,234 5 7 | |
| *Less* Depreciation (5 %) ... ... ... ... | 211 14 3 | |
| | | 4,022 11 4 |
| „ MUSEUM (Instruments purchased from the collection of the late Sir William Crookes) ... ... ... ... ... ... ... | | 213 12 6 |
| „ SUNDRY DEBTORS ... ... ... ... ... ... ... ... | | 2,270 1 7 |
| „ INSURANCE PREMIUMS AND SUNDRY PAYMENTS IN ADVANCE ... | | 911 10 9 |
| „ STOCK OF PAPER, ETC., FOR PUBLICATIONS ... ... ... ... | | 306 6 5 |
| Carried Forward ... ... ... ... | | 102,711 14 2 |

## BALANCE SHEET—*continued.*

**Dr.** LIABILITIES—*continued*

| | | £ s. d. | £ s. d |
|---|---|---|---|
| Brought Forward ... ... ... ... ... ... | | | 41,017 18 6 |
| To General Fund :— | | | |
| Balance at 1st January, 1922 ... ... ... | | 88,700 4 11 | |
| Amount of Life Compositions Fund (as per last Balance Sheet) now transferred to General Fund ... ... ... ... ... ... | | 5,590 10 0 | |
| Life Compositions received in 1922 ... ... | | 94 8 3 | |
| Obligatory Repayment to Economic Life Assurance Society ... ... ... ... ... | | 993 13 6 | |
| Voluntary Instalment repaid to Economic Life Assurance Society... ... ... ... ... | | 3,000 0 0 | |
| Expenditure in 1922 on— | | | |
| Books and Binding for Library ... ... | | 119 13 4 | |
| Furniture, Fittings and Apparatus ... ... | | 718 3 5 | |
| Balance from Revenue Account for 1922 ... | | 862 2 8 | |
| | | 100,078 16 1 | |
| *Less* Depreciation (*per contra*) :— | | | |
| Library ... ... ... ... | £116 12 9 | | |
| Furniture, Fittings, and Apparatus | 211 14 3 | | |
| | | 328 7 0 | |
| | | | 99,750 9 1 |
| | | | £140,768 7 7 |

JAMES DEVONSHIRE,
*Honorary Treasurer.*

P. F. ROWELL,
*Secretary.*

ASSETS—*continued.* **Cr.**

| | £ s. d. | £ s. d. |
|---|---|---|
| Brought Forward ... ... ... ... ... ... | | 102,711 14 2 |
| By General and Reserve Funds Investments (at cost)* :— | | |
| £2,600 Natal Zululand Railways 3% Debentures | 2,270 12 0 | |
| £1,500 London and North Western Railway 4% Preference Stock ... ... ... ... ... | 1,513 10 4 | |
| £2,000 Assam Bengal Railways 3% Stock ... | 1,548 0 6 | |
| £750 Western Australia 4% Stock ... ... ... | 730 8 3 | |
| £750 Union of South Africa 4% Stock ... ... | 742 12 0 | |
| £750 Madras and Southern Mahratta Railway 4% Debenture Stock ... ... ... ... ... | 738 15 6 | |
| £35 East Indian Railway "B" Annuity ... ... | 791 5 4 | |
| £1,500 South Australian 4% Stock ... ... ... | 1,494 10 6 | |
| £5,250 5% War Stock... ... ... ... ... | 4,987 10 0 | |
| £2,000 5% National War Bonds ... ... ... | 2,000 0 0 | |
| £19,375 4% Funding Loan ... ... ... ... | 15,500 0 0 | |
| £2,000 5¾% Exchequer Bonds ... ... ... | 1,991 9 0 | |
| | | 34,308 13 5 |
| „ Cash in Hands of Local Centres on 30 Sept., 1922 ... ... | | 513 12 11 |
| „ Cash :— | | |
| At Bankers' ... ... ... ... ... ... | 3,082 9 7 | |
| At Post Office Savings Bank (Uninvested Balance of David Hughes Scholarship Trust Fund) ... | 1 8 9 | |
| In hands of Secretary ... ... ... ... ... | 150 8 9 | |
| | | 3,234 7 1 |
| | | £140,768 7 7 |

* The above values are subject to depreciation.

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1922, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct, and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of the Institution.

ALLEN, ATTFIELD & Co., *Auditors,*
Chartered Accountants,
24, Martin Lane, Cannon Street, E.C. 4.

*7th May,* 1923

## SALOMONS SCHOLARSHIP TRUST FUND.

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount (as per last Account) ... ... ... | 2,126 | 19 | 3 | By Investments (at cost) :— | | | |
| | | | | £1,500 New South Wales 3½% Stock ... ... | 1,556 | 5 | 9 |
| | | | | £500 Cape of Good Hope 3½% Stock ... ... | 570 | 13 | 6 |
| | £2,126 | 19 | 3 | | £2,126 | 19 | 3 |

## SALOMONS SCHOLARSHIP TRUST FUND (Income).

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount paid to Scholars in 1922 ... ... | 87 | 10 | 0 | By Balance (as per last Account) ... ... ... | 58 | 1 | 5 |
| ,, Balance carried to Balance Sheet * ... ... | 40 | 14 | 11 | ,, Dividends received in 1922 ... ... ... | 70 | 3 | 6 |
| | £128 | 4 | 11 | | £128 | 4 | 11 |

## DAVID HUGHES SCHOLARSHIP TRUST FUND.

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount (as per last Account) ... ... ... | 2,000 | 0 | 0 | By Investment (at cost) :— | | | |
| | | | | £2,045 Staines Reservoirs 3% Guaranteed Debenture Stock ... ... ... ... ... | 1,998 | 15 | 0 |
| | | | | ,, Balance carried to Balance Sheet * ... ... | 1 | 5 | 0 |
| | £2,000 | 0 | 0 | | £2,000 | 0 | 0 |

## DAVID HUGHES SCHOLARSHIP TRUST FUND (Income).

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount paid to Scholars in 1922 ... ... | 47 | 10 | 0 | By Balance (as per last Account) ... ... ... | 37 | 19 | 5 |
| ,, Balance carried to Balance Sheet * ... ... | 51 | 14 | 0 | ,, Dividends received in 1922 ... ... ... | 61 | 4 | 1 |
| | | | | ,, Interest do. do. ... ... ... | 0 | 0 | 6 |
| | £99 | 4 | 0 | | £99 | 4 | 0 |

## PAUL SCHOLARSHIP FUND.

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount (as per last Account) ... ... ... | 500 | 0 | 0 | By Investment (at cost) :— | | | |
| | | | | £625 4% Funding Loan ... ... ... ... | 500 | 0 | 0 |
| | £500 | 0 | 0 | | £500 | 0 | 0 |

## PAUL SCHOLARSHIP FUND (Income).

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount paid to Scholar in 1922 ... ... | 12 | 10 | 0 | By Balance (as per last Account) ... ... ... | 25 | 0 | 0 |
| ,, Balance carried to Balance Sheet * ... ... | 37 | 10 | 0 | ,, Dividends received in 1922 ... ... ... | 25 | 0 | 0 |
| | £50 | 0 | 0 | | £50 | 0 | 0 |

---

* Included in the total of £360 19s. 4d. shown on the Liabilities side of the Balance Sheet.

## WILDE BENEVOLENT TRUST FUND.

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount (as per last Account) | 2,586 | 19 | 2 | By Investments (at cost) :— | | | |
| ,, ,, transferred from Income | 211 | 11 | 0 | £875 Great Eastern Railway Metropolitan 5% Guaranteed Stock | 1,493 | 10 | 3 |
| | | | | £215 North Eastern Railway 4% Guaranteed Stock | 250 | 19 | 9 |
| | | | | £100 London County 3½% Stock | 101 | 8 | 6 |
| | | | | £250 New South-Wales 4% Stock | 251 | 6 | 0 |
| | | | | £100 3½% War Stock | 94 | 8 | 8 |
| | | | | £100 5% War Stock | 95 | 0 | 0 |
| | | | | £381 15s. 1d. 4% Funding Loan | 300 | 0 | 0 |
| | | | | £200 5% National War Bonds | 211 | 11 | 0 |
| | £2,798 | 10 | 2 | | £2,798 | 10 | 2 |

## WILDE BENEVOLENT TRUST FUND (Income).

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount transferred to Capital | 211 | 11 | 0 | By Balance (as per last Account) | 194 | 14 | 5 |
| ,, Balance carried to Balance Sheet * | 79 | 15 | 5 | ,, Dividends received in 1922 | 94 | 5 | 8 |
| | | | | ,, Interest do. do. | 2 | 6 | 4 |
| | £291 | 6 | 5 | | £291 | 6 | 5 |

## WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1).

| Dr. | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Amount (as per last Account) | 1,700 | 0 | 0 | By Investment (at cost) :— | | | |
| | | | | £2,000 5% War Stock | 1,700 | 0 | 0 |
| | £1,700 | 0 | 0 | | £1,700 | 0 | 0 |

## WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Income).

| Dr | £ | s. | d. | Cr. | £ | s. | d. |
|---|---|---|---|---|---|---|---|
| To Grants made in 1922 | 75 | 0 | 0 | By Balance (as per last Account) | 125 | 0 | 0 |
| ,, Balance carried to Balance Sheet * | 150 | 0 | 0 | ,, Dividends received in 1922 | 100 | 0 | 0 |
| | £225 | 0 | 0 | | £225 | 0 | 0 |

---

* Included in the total of £360 19s. 4d. shown on the Liabilities side of the Balance Sheet

# PROCEEDINGS OF THE INSTITUTION.

## 692nd ORDINARY MEETING, 18 JANUARY, 1923

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 4th January, 1923, were taken as read and were confirmed and signed.

Messrs. A. Willmott and J. Bacon were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows :—

### Elections.

*Members.*

Brookes, Alfred, M.Eng.
King, Louis Herbert.
Sykes, Joseph Charles.

*Associate Members.*

Arnold, Hugh Turney.
Boex, George.
Bottomley, William Henry.
Buchanan, Andrew Duncan
Burton, Algernon.
Camozzi, Percy Joe.
Chadwick, Arthur.
Collins, Charles Frederick.
Dordi, Kersasp Mancherji, B.Sc.
Evans, Rees.
Evans, William Rhys, B.Sc.
Foley, John Laurence.
Gill, Harry.
Hallam, James Percy.
Harvey, Robert Gourlay.
Hay, William Ross, Capt., R.C.S.
Hayes, Patrick Joseph.
Herbert, Edward Dave A., O.B.E.
Hutchinson, Arthur James.
Jones, Richard Wilson.
Ketton, Harold Isaac.
Kirke, Percy St. George, M.A.
Lancaster, Walter Bernard.
Landau, Simon I.
Mackay, Thomas Whittaker, B.Sc.
MacLennan, Telford, B.Eng.
Moinet, John Vincent.
Morrish, Henry Edwin.
Nisbet, Richard William.
Owens, Ernest David C.
Ozanne, Major Guy Durand, M.C.
Peters, Charles Leonard, B.Sc. (Eng.).
Rawling, Arthur.
Richardson, Jocelyn Arthur S., B.A.
Scarr, William.
Smither, William James.
Tillson, Francis Joseph.
Walton, George Warren, B.A.
Watterson, Harold Edward.
Wilkins, Edward Henry.

*Graduates.*

Adie, Brooke.
Barrs, Herbert Harold.
Bechar, Shivji, B.Sc.
Billingsley, Frederick Thomas.
Boscolo, Gioachino Riccardo.
Briggs, Richard Alfred.
Burford, Gerald George.
Byatt, Arthur William.
Cairns, Archibald McFarlane, B.Sc.(Eng.).
Campbell, Frank Woodliffe.
Carter, Gordon Leonard.
Clarke, Wright William, B.Sc.(Eng.).
Clough, Newsome Henry, B.Sc.(Eng.).

*Graduates*—continued.

Cooke, Albert Sidney.
Corkill, Francis Malcolm, B.E., M.Sc.
Cox, Walter Ronald, B.E.
Desai, Becharbhai Purushotamdas, B.A., B.Sc.
Dobson, Albert Edwin.
Dowding, George Victor.
Fitton, Wilfred Robert.
Fitzsimmons, Arthur.
Fraser, William Lawrie.
Gabrielle, Harold Lionel.
Grapes, William Harvey H.
Hall, John Charles.
Havekin, Thomas, B.Sc.
Hunt, Kenneth Philip.
James, Richard Francis E.
Jenkin, Ralph Meredith.
Johnstone, Archibald.
Jones, David William G.
Judd, Maurice Frank.
Khory, Keki Nowerozji.
Kington, Arthur Charles.
Larkin, Charles Neville.
Latimer, George Wilfrid.
Lauder, John Robert.
Linsell, Alfred Aubyn.
Manighetti, Augustus.
Matthews, Mabel Lucy (Mrs.).
Moody-Smith, Claude Gerald.
Mowat, Eric Matheson.
Passmore, William Oglesby.
Patterson, John Harold.
Patterson, William Herbert.
Rawlings, Bernard Clarence.
Robinson, Henry John.
Roots, Albert Ernest.
Sang, Ram Parshad.
Smithells, Thomas Archibald, B.Sc.(Eng.).
Spruce, Samuel Raymond.
Summers, Albert Victor.
Suyling, Karel Lambertus.
Tonkin, Cecil Vivian.
Turner, Leonard Vivian.
Warder, Leonard Isaac.
Websdale, Geoffrey John.
Weygood, Wilfred.

*Students.*

Akehurst, John Reginald C.
Armstead, Hugh Christopher H.
Atkinson, Edmund Stroud P.
Axe, Leonard George.
Bailey, Philip Albert.
Baillie, Robert.
Barker, Wallace Henry.
Bartlett, Howard Volins.
Bass, Cyril Alfred.
Batt, Frederick Horace.
Beddoe, George Neville.
Bee, Oswald Kestor.
Bellasis, Guy Roland J.
Bennett, Harold John.
Berry, Anthony George.
Binns, Arthur William.
Bissell, Frank Edwin G.
Blake, Philip Kellow.
Bland, John George.
Blumlein, Alan Dower.
Bordewick, Olaf Unger.
Boul, Samson Augustine.
Bridgman, Howard Cecil.
Briggs, William Francis E.
Bristow, Geoffrey William.
Brockington, Hugh.
Brotherton, Francis.
Brown, Arthur Frederick C.
Brown, Guy Lawrence.
Buckingham, Alfred.
Bull, George Arthur.
Burnett, James.
Butterworth, Frank Scholfield.
Cann, Edward Thomas K.
Cathcart, David Maclaren.
Chalmers, William Ridgewell.
Choa, Chin Som.
Choudary, Vellanki Akkayya.
Christie, Charles Alexander.
Clibbon, Harold Alfred.
Coel, Frederick William.
Cogle, John Edmund T.
Coleman, William David.

*Students*—continued.

Collom, Frederick William.
Connard, Roland.
Connor, Vincent Edward.
Cook, Gerald Cloudesley.
Corbett, Francis William H.
Corke, Hugh Wernham.
Cottenden, Stanley Charles.
Cousins, George Cornelius.
Coutts, Charles.
Couzens, Jack Harold.
Cox, Percy Harold.
Crompton, Archie.
Cropley, Clyde Pembroke.
Crowley, Eric Conger.
Curtis, James Stanislas.
d'Assis-Fonseca, Harold Mountjoy M.
Davey, Cyril Frederick.
Davies, Evan Daniel.
Davies, William.
Dawson, Alfred John.
de Kretser, Horace Egerton S.
Dennis, Nigel Henry.
Dennison, James Derry.
Dickinson, John Clegg.
Downham, Albert Scott.
Dudley, Harold.
Dunthorne, John Doughty.
England, Charles James.
England, Philip Cuthbert.
Evans, Charles Herbert.
Eversfield, Henry Thomas L.
Farnes, Gilbert Henry.
Fawcett, Francis Alfred.
Fenemore, Alan Stephen.
Fletcher, Frederick George.
Follett, Samuel Frank.
Forster, Charles Edward.
Forster, William Johnston.
Foster, Thomas Leslie.
Francis, Maurice Hart.
Frost, Victor Henry.
Gachet, Ernest Jules.
Gairdner, William Douglas T.
Gibbs, William Ewart.
Gibson, Stanley.
Giles, Cecil.
Gledson, William Richard.
Goodall, Laurence.
Gooderham, Sydney John.
Gough, Ronald Eric.
Gould, John Ridd.
Gray, Thomas Anderson.
Grieve, John Watkin.
Griffiths, Patrick Edwin A.
Groves, Thomas Josiah.
Gunn, George John T.
Guthrie, David Ephraim.
Guy, Richard Francis W.
Halsey, Arthur Maurice.
Hampson, Arthur Eric.
Harbottle, Horace Reginald.
Harding, Eric Henry.
Harris, Arthur Cornfield.
Harrison, Clement Philip.
Hart, Stanley Haines.
Haworth, Percy S.
Heazell, Frederick Arthur.
Helme, James.
Henderson, Howard Rhodes.
Henderson, Victor Pringle.
Hendry, Alexander Wood.
Henry, Francis Bayly.
Hinshelwood, Cyril Eugene G.
Holliday, Frederick.
Hooker, Albert.
Hornby, James Hobson.
Hsu, Han Suan.
Humphries, Lawrence Milton.
Isterling, Jasper.
Jackson, Arthur Norman.
Jackson, William Graham.
James, Edward Edwin.
Johnson, Herbert Arthur.
Johnson, Reginald Arthur Josiah.
Johnstone, Andrew Wauchope.
Jones, Alfred John C.
Jones, Griffith Edgar.
Joseph, Samuel.
Joughin, Walter James.
Justin, Herbert Francis.
Kelly, Gerald Emil.
Kemp, Robert James A.
Kim, George Callum.
Knight, Arthur Reginald.
Kulkarni, Purushottam Parshuram.
Langley, John Edward.
Lawry, Arthur Vivian.
Leathes, William Henry B.
Lee, Leonard Staveley.
Lees, Stanley Binnington.
Lumby, Reginald Evelyn A.
Lyne, Harold Victor W.
McAlpine, James.
MacElwee, Norman MacLeod.
McKenzie, Angus Hugh.
McLennan, Roderick Arthur.
McQuarrie, Archibald.
Maggs, Arthur Hemborough.

*Students*—continued.

Malik, Amir Bakhsh.
Mansfield, Thomas James.
Marchbanks, Maurice James.
Mead, Edward Michael K.
Merrylees, Kenneth William.
Middlemiss, Reginald George.
Milling, Henry Robert.
Milne, Arthur John.
Mitchell, Valentine.
Morton, James.
Mountain, Reginald William.
Nadkarni, Anant Pandurang.
Newhouse, Kenneth Henry A.
Newton, Arthur Salt.
Newton, Geoffrey.
Nundy, George Reginald.
Olgin, Nicolas.
O'Meara, Esmonde.
Overington, Lionel Eric.
Paddle, Leslie Harold.
Padgett, George Thomas.
Padmanabhan, Catancolatur.
Paige, Henry Hodson.
Partridge, Norman George R.
Paterson, William Douglas.
Paul, Stanley Walter.
Pettersen, Johan August.
Piloyan, Andrew Jakovlevitch.
Poole, William Henry.
Poolman, Charles Grundy N.
Potter, Reginald Lewis.
Preston, Geoffrey William.
Price, Albert Eric.
Pyke, Edward Joseph.
Rackow, Charles.
Randall, Alfred Johnson.
Rantzen, Henry Barnato.
Rao, Domalpalli Venugopal.
Rao, Konsur Narayanarao Ranga.
Rawlings, Ralph John.
Reffell, John Robert.
Rentoul, Richard Laurence.
Rhodes, Cecil.
Richards, Thomas William.
Richardson, Richard Paul.
Riches, Albert John.
Robinson, Raymond.
Robinson, Richard Edward.
Rochester, William.
Rodda, William James.
Rodrigues, John Rozario.
Rogers, Alec Hugh G.
Rogers, Victor John.
Rothwell, Stanley R.
Rowe, Charles.
Roy, Kamala Prasanna.
Ryall, Ernest Roberts S.
Sayers, Arthur Joe.
Scott, Dan.
Shaw, James Ernest.
Shuttleworth, John Henry.
Simons, Evelyn John.
Slann, Louis Alfred J.
Slater, Kenneth Algernon H.
Smart, Henry Prescott.
Smedley, Philip Henry.
Smillie, John.
Smith, Frederic Rowland C.
Smith, Roderick Alan.
Soper, Robert Edwin S.
Sparks, Ronald Allison.
Srinivasan, Mandayam Thondanore.
Steel, Robert William.
Stobart, Leslie Wallace.
Stripe, Norman Albert.
Swann, Joseph Eric.
Tamplin, Struan Robertson.
Taylor, Richard Lough.
Terroni, Teseo Bruno D.
Thadhani, Hotechaud Rijhumal.
Thomas, Philip Robert.
Thompson, Harry Ernest.
Tibbatts, William Albert.
Treharne, John Stewart E.
Trueman, Raymond Shaw.
Tyler, Leslie Norman.
Vigoureux, Joseph Evenor P.
Vines, Murray.
Viney, Hallen.
Waggott, Harry Cuthbert.
Wallace, Douglas Stewart.
Warman, Arthur Charles.
Warrington, Albert Russell V.
Waters, George.
Watkins, Donald John.
Watling, Hugh Henry W.
Welchman, Philip Raymond.
Wellsteed, Albert Edward.
Westlake, Harry James M.
Whiteside, William Hayes.
Whiteway, George Henry.
Williams, Harold George.
Williams, Thomas.

*Students*—continued.

Williamson, Peter Blanche.
Willis, Albert Henry.
Willoughby, Ralph.
Wilmot, Reginald Hilton.
Winborne, James Ernest.
Wolfe, John.
Woodward, George Lawrence.
Wooler, Clifford Upton.
Wright, Rowland.
Young, Alexander.
Young, William.

*Associates.*

Marreco, Geoffrey Freire.
Reynolds, Russell John, M.B., B.S.
Yarrow, Harold Edgar.

### TRANSFERS.

*Associate Member to Member.*

Browne, Bernard Frederick.
Cockshott, Edgar Harry.
Dayson, Albert Ogden, M.C.
Denehy, Hugh.
Dixon, Harry.
Evans, Arthur Anthony, Lt.-Col., O.B.E., M.C., R.E.
Gatehouse, Ernest Arthur.
Green, Harry.
Hedgcock, Archibald John.
Homan, Franklin Thomas.
Howe-Gould, Robert.
Mallett, Edward, M.Sc. (Eng.).
Meikle, James.
Mitchell, Raymond James.
Moore, William Alexander.
Pook, Stanley Herbert.
Rosen, Jessel.
Taylor, Claude Sinclair.

*Graduate to Associate Member.*

Cotton, Harry.
Dedley, William John F.
Duckworth, Herbert.
Edwards, Arthur Rowland.
Edwards, John Marshall, B.Sc.(Eng.).
Kay, Henry Herbert.
Llewellyn-Jones, Ivor.
Lye, Donovan Henry C.
McClean, Thomas.
Monk, Sidney Gordon, B.Sc.
Otter, Francis Lewis, M.C.
Pallot, Arthur Charles, B.Sc.(Eng.).
Sadleir, John Rothwell.
Smith, Clarence Herbert.
Wilkinson, Harold Claud.

*Student to Associate Member.*

Baldwin, Sydney James W.
Clyne, Philip.
da Silva, Pery Roma.
Diggle, Harold.
Frost, Ronald Arthur.
Glover, Eric Harraden.
Greenwood, Walter.
Kennaird, George William.
Mould, James.
Parkinson, Arthur Muir, B.Sc.(Eng.).
Ramsdale, William Stanley.
Robinson, Geoffrey.
Waizbom, Harold.

*Associate to Associate Member.*

Hungerford, Richard Becher.
Kennard, Hammond Levene E.
Millar, Charles Herbert.
Robinson, Samuel Thomas.

*Student to Graduate.*

Arnold, John Frank, Lieut.
Barnes, William Charles.
Bawtree, Edward.
Baxendell, Leslie Wilfred E.
Bellamy, Fenton George.
Bleach, Chris Charles.
Braendle, Ernest William.
Brierley, Herbert.
Carter, Henry Edmond D.
Charman, Cyril Edward.
Combes, Frank Roy, B.E.
Craig, Samuel.
Dawes, Arthur Robert.
Doran, William Ernest.
Edwards, Wilfrid Gordon.
Ellis, Francis Arthur.
Fletcher, Godfrey Herbert.
Frampton, Harold George.
Hartley, Robert Cliff.
Jackson, Frederick Stanley.
Janmoulle, Edward Walter A.
Jenkins, William Arthur.
Maxfield, George William.
Nicholson, Frederick Walter.
Nicholson, Hugh John G., B.Eng.
Pankhurst, Frank Arthur.
Parker, Alfred Henry.
Parnall, Eric John.
Pittaway, Kenneth.
Read, Grosvenor Woodhouse.
Seymour, James Edward.
Sundaram, Gangadhara.
Templeton, William.
Waddicor, Harold.
Wallace, Robert, B.Sc.
Welch, Leonard John.
Young, James Buchan, B.Sc.

The President mentioned that successful wireless telephonic communication between New York and London had been effected for a period of two hours on the previous Monday morning, 15th January, and that among the messages transmitted was one from Mr. Carty, Past-President of the American Institute of Electrical Engineers, who, on behalf of Dr. Jewett, President of that Institute, sent his best wishes to the British Institution of Electrical Engineers and said that electrical engineers were very proud to be able to do so much to bring all nations closer together by means of wireless communication. The President also mentioned that he had replied by telegram to Dr. Jewett, as follows: "Most sincere and fraternal greetings from your British confrères."

A paper by Mr. G. H. Nelson, Member, entitled "Works Production" (see page 338) was read and discussed, and the meeting terminated at 8.5 p.m.

---

## 693RD ORDINARY MEETING, 1 FEBRUARY, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 18th January, 1923, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read, and was ordered to be suspended in the Hall.

The President presented to Mr. J. W. Meares, C.I.E., Member, late Local Hon. Secretary of the Institution in India, and Electrical Adviser to the Indian Government, a salver and cigarette box subscribed for by his friends in India on the occasion of his retirement from the Indian Government service, and as a token of his valuable services to the profession in India.

A paper by Mr. P. J. Robinson, Associate Member, entitled "The Maintenance of Voltage on a D.C. Distribution System by means of a Fully Automatic Substation" (see page 417), was read and discussed, and the meeting terminated at 7.45 p.m.

# THE FOURTEENTH KELVIN LECTURE.

## PROBLEMS IN TELEPHONY, SOLVED AND UNSOLVED.

By Professor J. A. Fleming, M.A., D.Sc., F.R.S., Honorary Member.

(*Lecture delivered before* The Institution, 10*th May*, 1923.)

### Syllabus.

I. *Introductory.*—Lord Kelvin and the invention of the speaking telephone by Alexander Graham Bell in 1876.

II. *Sound-wave energy.*—Definitions of acoustic quantities, and mathematical expressions for sound-wave energy in terms of them.

III. *Sound-wave amplitude and condensation necessary for audition.*—Researches of Lord Rayleigh, Wien, and others. Investigations by Minton, Lane, Fletcher and Wegel. Frequencies for which the ear is most sensitive. Energy expenditure in the production of aerial speech waves.

IV. *Nature of speech sounds.*—Phonetic analysis of speech sounds. The *articulation* of a telephone system. Researches of Fletcher on the telephonic transmission of speech, and the effect on it of filtering out certain ranges of frequency. Theories of audition. The function of Corti's organ in the ear.

V. *The telephone considered as an energy-transforming device.*—The natural frequency of a circular diaphragm. Kennelly's statement of the four fundamental constants of a magneto-receiver. Motional resistance and impedance. The amplitude of motion of the diaphragm. Formulæ for the acoustic efficiency of a Bell receiver. Causes of its inefficiency. Possible substitutes.

VI. *The transmission problems of the telephone line.*—Heaviside's theory. The introduction of the dry-core lead-sheathed cable. Pupin's contributions and inventions. Coil loading of aerial and underground lines. Loading of submarine cables by coil, and uniform loading. Key West–Havana loaded, deep-sea telephone cable.

VII. *The problem of the telephone repeater.*—The theory of the thermionic valve, and its application as a telephone repeater. Types of valve employed. Measurements of repeater gain, in miles of standard cable. Repeater connections and stations.

VIII. *The problem of multiple telephony.*—Phantom working and loading of phantom circuits. Principles of carrier-wave telephony. Methods of modulation and demodulation by thermionic valves. Suppressed carrier-wave telephony and multiplex working.

IX. *The problems of commercial telephony.*—The common-battery system. The evolution of the multiple switchboard and manual exchanges. Automatic exchanges.

X. *Some problems of radio-telephony.*—Recent improvements in thermionic valves, for small- and large-power generation. The problems of radio-telephony over short, medium and long distances. Short-wave mirror-directed radio-telephony. Interconnection of exchange circuits by radio. Recent achievements in long-distance radio-telephony.

XI. *Conclusion.*—The importance of scientific research in connection with the telephone industry. Desirability of encouraging private as well as State-supported research in this subject. The wide field for future work.

Appendices I and II.

### I. Introductory.

(1) In looking back at the titles of previous Kelvin Lectures it is noticeable that one subject, in which the late Lord Kelvin took a profound interest from its earliest days, has not yet received attention in them, viz. that of Telephony or the transmission of articulate speech to a distance by electrical means.

I well remember, as if it were only yesterday, though it is in fact 47 years ago, sitting close in front of Lord Kelvin when as Sir William Thomson he gave the Introductory Address to Section A of the British Association, then meeting in Glasgow, when he described to us his first acquaintance with Bell's great invention, the speaking telephone. Lord Kelvin had just returned from the United States where he had been one of the scientific judges at the Centennial Exhibition at Philadelphia in June 1876. Addressing us he said :—

> "In the Canadian Department I heard 'To be or not to be, there's the rub,' through a telegraph wire; but scorning monosyllables the electric articulation rose to higher flights and gave me passages taken at random from the New York newspapers, such as 's.s. *Cox* has arrived' (I failed to make out s.s. *Cox*); 'The Senate has resolved to print a thousand extra copies'; 'The Americans in London have resolved to celebrate the coming Fourth of July.' All this my own ears heard spoken with unmistakable distinctness by the thin circular disc armature of just such another little electromagnet as this which I hold in my hand. The words were shouted with a clear, loud voice by my colleague Judge, Professor Watson, at the far end of the telegraph wire, holding his mouth close to a stretched membrane, such as you see before you here, carrying a little piece of soft iron which was made to perform in the neighbourhood of an electromagnet in circuit with the line motions proportional to the sonorific motions of the air. This, the greatest by far of all the marvels of the electric telegraph, is due to a young countryman of our own, Mr. Graham Bell, of Edinburgh and Montreal and Boston, now becoming a naturalized citizen of the United States. Who can but admire the hardihood of invention which has devised such very slight means to realize the mathematical conception that, if electricity is to convey all the delicacies of quality which distinguish articulate speech, the strength of its current must vary continuously and as nearly as may be in simple proportion to the velocity of a particle of air engaged in constituting the sound."

In the year therefore following that of the decease of the illustrious inventor of the speaking telephone it is perhaps appropriate that the Kelvin Lecture should direct attention to some of the problems of telephony which have been solved, or which remain unsolved in the nearly half-century which has elapsed since the above quoted words were uttered by Lord Kelvin.

Since the reproduction of articulate speech at a distance necessitates the creation of air waves and this requires the expenditure of energy, it will be convenient to start with a statement of the physical relations of the measurable quantities with which we are concerned, and of the methods by which we can determine the energy expenditure in creating audible and articulate sounds.

### II. SOUND-WAVE ENERGY.

(2) When a sound wave is passing through the air, if the sound is a continuous one, there is at any point in the field a rapidly repeated change of air pressure which periodically rises above or falls below the normal static pressure of the air, as determined by the barometric height at that moment, which is approximately 14½ lb. per square inch, or about 1 megadyne per square centimetre in C.G.S. measure. There is therefore a variable pressure superimposed on a steady pressure and we may define the conditions by stating the R.M.S. value of the variable part of the pressure in absolute units or by the ratio of the maximum of the variable part to the steady pressure.

In a sound wave we have also periodic variation of air density at any point, and hence another way of defining the acoustic state is by the variation in air density which occurs. If $\rho$ is the normal density of the air and $\rho'$ the increased or reduced density, then the ratio $(\rho' - \rho)/\rho = s$ is called by the late Lord Rayleigh and other writers the *condensation* at that point. The condensation takes place in consequence of a pendulum-like motion of the air particles to and fro in the direction of propagation of the wave. It is usual to consider the maximum condensation during the periodic change. If for the sake of simplicity we confine our attention to propagation in one direction, or consider the case of a parallel beam of sound or propagation through a straight tube, then we can easily obtain an expression for the rate at which energy is being transmitted across each square centimetre of the tube cross-section.

For it is clear that this is equal to the mean value of the product of the air velocity in the direction of the wave, and the variable pressure.

Problems in acoustics are in many cases best treated by the use of a quantity called the *velocity potential*, which is a function of time and space such that its space rate of change in a certain direction gives us the acoustic velocity of the air particles in that direction (see Appendix I). In the case of a plane sine-form wave due to a pure musical sound propagated in the direction of the $x$-axis, the velocity potential $b$ is expressed by :—

$$b = B \cos (mx - \omega t) \quad . \quad . \quad . \quad . \quad (1)$$

where $m = 2\pi/\lambda$ and $\omega = 2\pi n$, $\lambda$ being the wave-length and $n$ the frequency of the sound wave. Hence, differentiating (1) with respect to $x$, we have the velocity of the air particle in that direction.

Let it be denoted by $\dot{a}$ where the dot denotes time rate of change of displacement $a$. Then

$$\frac{da}{dt} = \dot{a} = \frac{db}{dx} = - mB \sin (mn - \omega t) \quad . \quad (2)$$

Hence the displacement $a$ is obtained by integrating (2) with respect to time, thus :—

$$a = \frac{mB}{\omega} \cos (mx - nt) \quad . \quad . \quad . \quad (3)$$

Therefore, if $A$ is the maximum displacement or amplitude, $A = mB/\omega = B/c$, where $c$ stands for the velocity of sound. It is shown by the late Lord Rayleigh in his " Treatise of Sound " (vol. 2, § 244, p. 14) that if $\rho_0$ is the normal density of the air and $p$ the variable part of the pressure, then, in the absence of other impressed forces :—

$$p = - \rho_0 \frac{db}{dt} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The energy transmitted per second by the wave through 1 square centrimetre normal to the line of propagation, is the mean value throughout a period of the product $p\dot{a}$.

Now,
$$\frac{db}{dt} = \omega B \sin (mx - \omega t) \quad . \quad . \quad . \quad (5)$$

Therefore from (2), (4) and (5), and bearing in mind that the mean value of $\sin^2 \theta$ throughout a period is ½, we have for this mean rate of transfer of energy :—

$$W = \tfrac{1}{2} \rho m \omega B^2 \quad . \quad . \quad . \quad . \quad . \quad (6)$$

If $c$ denotes the velocity of sound, $c = \omega/m$, then, since $A = mB/\omega$, (6) may be written :—

$$\begin{aligned} W &= 2\pi^2 \rho_0 c n^2 A^2 \quad . \quad . \quad . \quad . \quad (7) \\ &= \tfrac{1}{2} \rho_0 c \omega^2 A^2 \end{aligned}$$

The normal density of air is $\rho_0 = 0 \cdot 00129$ g/cm$^2$ and the velocity of sound in air at 0° C. and 760 mm is $c = 3 \cdot 3 \times 10^4$ cm/sec. Also, $2\pi^2 = 19 \cdot 75$ and, therefore,

$$W = 840 \cdot 75 n^2 A^2 \quad . \quad . \quad . \quad . \quad (8)$$

where $n$ is the frequency and $A$ is the maximum displacement of the air particle by the sound wave during its excursion. If we denote the maximum value of the velocity of the air particle by $\dot{A}$, then it is obvious from (5) that $\dot{A} = mB$ and that $\dot{A} = \omega A$.

If we assume that we are dealing only with pure musical sounds having a simple sine wave-form, then the root-mean-square (R.M.S.) value of any variable is $1/\sqrt{2} = 0 \cdot 7$ of its maximum value. Then from (2), (4) and (5) it is seen that :—

$$(\text{R.M.S.}) p = \frac{\rho \omega B}{\sqrt{2}} \quad . \quad . \quad . \quad . \quad (9)$$

$$(\text{R.M.S.}) \dot{a} = \frac{mB}{\sqrt{2}} = \frac{\dot{A}}{\sqrt{2}} \quad . \quad . \quad (10)$$

The expression (9) is the root-mean-square value of the variable part of the pressure, and (10) the same for the air particle velocity. Also by (6):—

$$W = (\text{R.M.S.}p)\,(\text{R.M.S.}\dot{a}) \quad . \quad . \quad (11)$$

From the above formulæ it follows that:—

$$(\text{R.M.S.})p = \sqrt{(\rho_0 c)}\sqrt{W} \quad . \quad . \quad . \quad (12)$$

$$(\text{R.M.S.})\dot{a} = \frac{\sqrt{W}}{\sqrt{(\rho_0 c)}} \quad . \quad . \quad . \quad . \quad (13)$$

The value of $\rho_0 c$ in C.G.S. units is 42·57, and $\sqrt{(\rho_0 c)} = 6 \cdot 5$ (nearly).

If the pressure ($p$) is measured in dynes per square centimetre then the energy ($W$) transmitted through 1 square centimetre per second is in ergs, and the velocity $\dot{a}$ in cm per second, then:—

$$(\text{R.M.S.})p = 6 \cdot 5\,\sqrt{W} \quad . \quad . \quad . \quad (14)$$

$$(\text{R.M.S.})\dot{a} = \frac{\sqrt{W}}{6 \cdot 5} \quad . \quad . \quad . \quad . \quad (15)$$

and

$$(\text{R.M.S.})p = 188 \cdot 5nA \quad . \quad . \quad . \quad (16)$$

If $s$ denotes the *condensation*, defined as above, it is shown in treatises on acoustics that $cs = \dot{a}$, where c is the velocity of sound. Hence, if $S$ is the maximum value of the condensation, $cS = \dot{A} = \omega A$, and also $S = (\omega/c)A$.

The above formulæ give us the means of making interesting deductions from experimental results as to the variation of air pressure and amplitude of motion of the air particles in a sound wave.

In using these formulæ it is necessary to bear in mind that, since the changes of pressure in an air wave are very rapid, the heat due to compression has not time to escape. Hence the pressures are adiabatic values and by the gas theory are equal to $\gamma$ times the isothermal pressures, where $\gamma = 1 \cdot 41$ is the ratio of the two specific heats of air. Therefore $p = \gamma s = 1 \cdot 41s = \sqrt{(2)}s$ (nearly). Since $\gamma$ is nearly equal to $\sqrt{2}$ it follows that for pure musical sounds the R.M.S. value of the variable part of the pressure is equal to the maximum value of condensation.

## III. Sound-wave Energy and Amplitude Necessary for Audition.

(3) During the last fifty years a large amount of research work has been done in determining the aerial wave energy per square centimetre per second which must be passing at a certain frequency, in order that the ear may just perceive it as an audible sound, or, alternatively, a sound of a certain pitch and loudness. In 1870 Töpler and Boltzmann[*] made one of the earliest determinations with an organ pipe of pitch 181, and found for the maximum compression $S$ a value $S = 6 \cdot 5 \times 10^{-8}$. The corresponding R.M.S. pressure is about 1/15 dyne per cm$^2$ when the sound was just audible. In 1877, Lord Rayleigh[†] used a whistle blown under a pressure of 9·5 cm of water taking 196 cm$^3$ of air per second and giving a sound of frequency $n = 2\,730$. The work done per second in blowing the whistle was then $196 \times 9 \cdot 5 \times 981 = 1\,826\,622$ ergs. He found that the whistle could just be heard in the open air in all directions at a maximum distance of 821 metres. Assuming all the energy to be expended in sound production and to be equally distributed over the hemisphere surface this gave the value of the wave energy ($W$) in ergs per cm$^2$ per second as 43 micro-ergs. Then from formula (7):—

$$W = \tfrac{1}{2}\rho c \omega^2 A^2$$

and from the relations $\dot{A} = A\omega$ and $S = \dot{A}/c$, where $\dot{A}$ is the maximum velocity of the air particle, $A$ its maximum displacement and $S$ the maximum condensation, he found at once $\dot{A} = 0 \cdot 0014$ cm/sec., $A = 8 \cdot 1 \times 10^{-8}$ cm and $S = 4 \times 10^{-8}$. The R.M.S. value of the variable pressure is then 0·04 dyne per cm$^2$.

This result showed how extremely small is the amplitude of periodic motion of an air particle which can produce a just audible sound. A length of $10^{-8}$ cm is called 1 Ångström unit (Å.U.); the length of a wave of yellow light is about 5 000 Å.U. and the diameter of a molecule about 1 or 2 Å.U. The maximum displacement of the air particle in the above case was only 8 Å.U., or about 1/600th of the length of a wave of yellow light.

(4) There are objections, however, to measurements made over large distances in open air, and hence in 1894 Lord Rayleigh employed a tuning fork of frequency 256 as a source of sound and determined the rate of energy emission from the rate of decay of the oscillations.[*] He found that when the fork was emitting sonorous energy at the rate of 42·1 ergs per second it could just be heard at a distance of 27·4 metres. This gives a mean density of wave energy per second over the hemisphere of 0·9 micro-erg per cm$^2$.

Calculating from the above formulæ the maximum amplitude and condensation for just audible sound waves, he found $A = 12 \cdot 7 \times 10^{-8}$ cm and $S = 0 \cdot 6 \times 10^{-8}$ at a frequency of 256. In 1894 Lord Rayleigh made a third measurement by the aid of a telephone receiver.[†] He measured the displacement of the diaphragm when a certain direct current was passed through the coils. He measured also the displacement of the diaphragm produced by a certain mechanical force reckoned in grammes weight applied to it, and from these figures he inferred that an alternating current of 0·83 microampere at a frequency of 256 p.p.s. produced a deflection of $6 \cdot 8 \times 10^{-8}$ cm $= 6 \cdot 8$ Å.U. at the centre of the diaphragm. He estimated that the effective area of the telephone diaphragm in producing sound waves was 4 cm$^2$, and that the volume of the cavity of the external ear contained between the ear-drum and the diaphragm of a telephone pressed against the ear was 20 cm$^3$. Hence it follows that the maximum condensation $S$ was $1 \cdot 4 \times 10^{-8}$ at a frequency of 256, and the corresponding amplitude of the air particle $2 \cdot 9 \times 10^{-7}$ cm. Lord Rayleigh's three experiments therefore gave for the condensation and amplitude of the just audible sound the following values :—

---

[*] *Annalen der Physik*, 1870, vol. 141, p. 321.

[†] *Proceedings of the Royal Society*, 1877, vol. 26, p. 248.

[*] *Philosophical Magazine*, 1894, vol. 38, p. 365.

[†] *Ibid.*, 1894, vol. 38, p. 295.

By whistle at $n = 2\,730$; $S = 4 \cdot 1 \times 10^{-8}$, $A = 8 \cdot 1 \times 10^{-8}$ cm.
By tuning fork at $n = 256$; $S = 0 \cdot 6 \times 10^{-8}$, $A = 12 \cdot 7 \times 10^{-8}$ cm.
By telephone at $n = 256$; $S = 1 \cdot 4 \times 10^{-8}$, $A = 29 \times 10^{-8}$ cm.

Approximately speaking we may say that at a frequency of 256 the ear detects as sound a periodic change in air density of 1 hundred-millionth of an atmosphere, an amount equal to the air density in a space exhausted to a very good vacuum. Also we appreciate an amplitude of motion of an air particle of 1 or 2 millionths of a millimetre and an energy stream of 1 to 3 micro-ergs or so per square centimetre per second.

It is obvious that a personal element of ear sensitiveness enters into these determinations of the pressure of the least audible sound.

It is not, therefore, surprising that very great differences appear between the results of different observers.

Thus Max Wien published a paper in 1903 " On the Sensitivity of the Human Ear for Tones of Various Frequencies," [*] in which he gave the results of measurements made with a telephone receiver. He determined the maximum of the variable part of the air pressure producing just audible sounds of various frequency. Translating Wien's results into condensation and amplitude (maximum values) we have the following :—

| Frequency, $n$ | Condensation, $S$ | Amplitude, $A$ |
|---|---|---|
| p.p.s.<br>50 | $11 \cdot 4 \times 10^{-8}$ | $117 \times 10^{-7}$ |
| 100 | $7 \cdot 8 \times 10^{-9}$ | $4 \cdot 2 \times 10^{-7}$ |
| 200 | $7 \cdot 2 \times 15^{-10}$ | $1 \cdot 8 \times 10^{-8}$ |
| 400 | $8 \cdot 6 \times 10^{-11}$ | $1 \cdot 13 \times 10^{-9}$ |
| 800 | $1 \cdot 6 \times 10^{-11}$ | $1 \cdot 1 \times 10^{-10}$ |
| 1 600 | $1 \cdot 0 \times 10^{-11}$ | $3 \cdot 3 \times 10^{-11}$ |
| 3 200 | $1 \cdot 0 \times 10^{-11}$ | $1 \cdot 6 \times 10^{-11}$ |
| 6 400 | $1 \cdot 6 \times 10^{-11}$ | $1 \cdot 3 \times 10^{-11}$ |
| 12 800 | $5 \cdot 7 \times 10^{-11}$ | $2 \cdot 3 \times 10^{-11}$ |

These figures show a decided maximum in ear sensitivity in the neighbourhood of the frequency 2 000 p.p.s.

Lord Rayleigh again returned to the subject in 1907, and in an article [†] on " The Relation of the Sensitiveness of the Ear to Pitch " he showed by a new method that the condensations corresponding to just audible sounds of frequencies, 85, 128, 256, 512, were in the ratio of 6·4, 3·2, 1·6 and 1.

He came to the conclusion that the ear had a maximum sensitivity at a frequency of about 1 000.

(5) Some recent researches aided by better instrumental appliances, and especially by the invaluable thermionic valve, have enabled this matter to be more fully explored.

It is abundantly clear from this later work that the human ear possesses a well-marked supersensitivity to sounds of certain frequency. One of these regions generally lies within the limits 700 to 1 000 p.p.s. and another between 1 500 and 2 000 p.p.s., and some observers indicate a third region about 3 500 to 4 000 p.p.s. There are, however, considerable variations in normal ears in this respect. This has been well shown in a paper [*] by J. P. Minton on " Physical Characteristics of Normal Ears."

He employed a telephone receiver with a diaphragm having a very high natural frequency (5 215 p.p.s.) and placed it in the bridge circuit of a Wheatstone bridge supplied with alternating currents of pure sine wave-form by means of a thermionic-valve generator with appropriate frequency filters. He calculated from the observed constants of the telephone the vibrational energy of the diaphragm for various bridge settings, and the sensitivity of the ear was taken to be inversely as the vibrational energy when the telephone was emitting a just audible sound at a certain frequency. He found as above mentioned that there are well-marked regions of supersensitivity in normal ears for certain frequency ranges.

The ear sensitivity diminishes very rapidly as the frequency rises much above 4 000 or 5 000 p.p.s. Thus, C. E. Lane,[†] using a particular type of sound producer called a " Tone Generator," invented by C. W. Hewlett,[‡] found that at a frequency of 2 000 p.p.s. the just audible sound to normal ears conveyed in wave energy 0·07 micro-erg through each square centimetre per second, but that when the frequency was raised to 18 000 or 20 000 it required an energy stream of 0·1 erg per square centimetre per second or nearly $1\frac{1}{2}$ million times as much power to produce the just audible sound.

A very complete examination of this question was made in 1922 by H. Fletcher and R. L. Wegel in a paper [§] on " The Frequency-sensitivity of Normal Ears," working in the research laboratories of the American Telephone and Telegraph Company and of the Western Electric Company, U.S.A. They used an air-damped telephone receiver and passed through it various pure sine-wave currents supplied by a thermionic-valve generator. The generator had its current filtered so as to eliminate all harmonics and produced an absolutely pure tone. This is an important precaution because a tone at 100 frequency requires 60 times greater pressure variation or 3 600 times greater energy to be just audible than a tone at a frequency of 1 000. They also constructed a particular form of artificial telephone line by which the current passing through the receiver could be weakened in an exactly known ratio. As a means for absolute calibration they used a condenser transmitter. This instrument is an improvement and modification of Dolbear's electrostatic transmitter. It consists of a fixed, solid, perfectly flat plate in front of which and parallel to this but about one-thousandth of an inch, or less, apart is held a thin, flexible, tightly strained steel disc. The thin and thick plates are insulated from each other and form an air condenser. If an alternating potential difference is applied to the plates, the flexible plate vibrates and emits a musical sound.

---

[*] See *Pflüger's Archives*, 1903, vol. 97, p. 1.

[†] *Philosophical Magazine*, 1907, vol. 14, ser. 6, p. 596.

[*] *Physical Review*, 1922, vol. 19 (2), p. 80.

[†] *Ibid.*, 1922, vol. 19, p. 492.

[‡] *Ibid.*, 1922, vol. 19, p. 52.

[§] *Ibid.*, 1922, vol. 19 (2), p. 553.

If, on the other hand, the plates are kept charged by a battery through a high resistance, and if the flexible plate is caused to vibrate by sound waves, the capacity of the condenser is periodically varied and hence the potential difference at the ends of the resistance also varies. This small varying potential difference can be amplified by thermionic valves and measured on a suitable thermo-electric voltmeter.

Hence the condenser transmitter can be calibrated by operating on it with known pressure variations and then used to produce sounds having known condensations and frequencies.

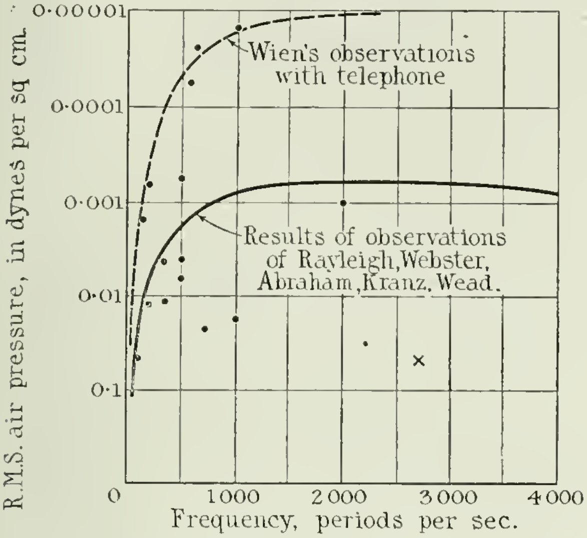


Fig. 1.—Curve showing by its ordinates the root-mean-square values of the variable part of the air pressure in an air wave producing a just audible sound, plotted in terms of frequency.

Note.—The cross indicates the result obtained by Lord Rayleigh in his experiment with the whistle.

The theory of the instrument has been fully discussed by E. C. Wente [*] in a paper on "A Condenser Transmitter as a Uniformly Sensitive Instrument for the Absolute Measurement of Sound Intensity."

In an instrument used in the research laboratories of the American Telephone and Telegraph Company, U.S.A., the diaphragm consisted of a steel disc 0·007 cm in thickness and 4·5 cm in diameter, having a natural frequency of 17 000 p.p.s. The air-gap was 0·0022 cm in thickness and could withstand a pressure of 320 volts, direct current. The condenser capacity was 335 $\mu\mu F$. Aided by this appliance Fletcher and Wegel showed that at a frequency of 60 p.p.s. the R.M.S. value of the variable part of the air pressure corresponding to a just audible sound was 0·15 dyne per cm². At a frequency of 1 000 p.p.s. it was 0·001 dyne per cm².

There are great individual variations and those who are not usually called deaf may require a variable pressure up to more than 0·1 dyne per cm² at 1 000 p.p.s., whilst those who are deficient in powers of audition may require even up to 1 to 10 dynes per cm² to hear the sound. Fletcher and Wegel embodied the results of various observers in a curve showing the R.M.S. pressures for the least audible sound at various frequencies (see Fig. 1). The condenser transmitter also enables us to measure the energy conveyed across unit area per second by air waves of the speaking voice.

In a paper [*] on "The Analysis of the Energy Distribution in Speech," by L. B. Crandall and D. Mackenzie, these observers found that at a distance of 1 inch from the mouth of a speaker in ordinary conversational tone the R.M.S. value of the variable part of the pressure due to speech waves was 11·3 dynes per cm². This corresponds to an energy flow of 3·2 ergs per cm² per second. E. C. Wente [†] found a similar value, viz. 10 dynes per cm² at 3 cm distance.

Assuming the energy to flow out equally over the surface of a hemisphere of 2·5 cm radius with centre on the lips, this amounts to a total energy emission of 125 ergs per second. If we assume the speaking to be kept up for 1 hour, the energy represented by such speech waves would only amount to 1/20 joule or 1/27 ft.-lb. of work. Even if we consider the wave amplitude to be increased 20 or 25 times, as might be the case in loud speaking or public lecturing, the total production of air-wave energy in the form of speech might only amount to 20 or 25 ft.-lb. in an hour. The total bodily energy expenditure as roughly judged by the fatigue of speaking to a large audience for an hour, even apart from bodily movements, is probably much greater. This gives an indication that the human vocal organs, considered simply as an energy-translating device for the production of speech-wave energy, may have small efficiency in the technical sense of the term.

## IV. The Nature of Speech Sounds, and the Operation of the Ear.

(6) The possible improvements in telephony are very closely dependent upon a knowledge of the nature of speech sounds and of the operation of the ear in appreciating them. A careful study of the problem of phonetics in its relation to telephony has been made during the past few years in the United States. The important matter, from the telephonic point of view, is the study of the frequency-ranges required to convey specific articulate sounds with adequate reproduction at the receiving end.

Broadly speaking, phoneticians divide the elements of speech sounds into five divisions: (1) Pure vowels, (2) combinational and transitional vowels (indicated by the letters w, y, long i, h and ou); (3) semi-vowels, l and r; (4) consonants, voiced, unvoiced, and nasalized; and (5) fricative consonants, voiced and unvoiced. A very rough distinction between the vowel and consonant sounds is that the former can be uttered continuously as long as one has breath, but the latter are more or less abrupt beginnings or endings of vocal sounds.

---

[*] See *Physical Review*, 1917, vol. 10 (2), p. 39.

[*] See *Physical Review*, 1922, vol. 19 (2), p. 221.

[†] *Ibid.*, 1922, vol. 19, p. 502.

The elements of all spoken languages are syllables, which are composed of combinations of the vowel and consonant sounds. Words are built up of syllables. The telephonic conveyance of speech depends, therefore, upon the accuracy of reproduction of the syllabic sounds at the receiver. In order to test this reproduction, telephonic engineers, in connection with the American Telephone and Telegraph and Western Electric engineers, prepared large lists of syllabic sounds comprising from 8 000 to 9 000 speech sounds in all, arranged in groups of 50 or 100.

A large number of these syllables are spoken in succession clearly to a transmitter. A listener at the receiver writes down the syllable received according to a certain code-word associated with it. The percentage of sounds correctly heard and written down is called the *articulation* of the system.

An account of certain research work of the above kind has been described by Harvey Fletcher in a paper * on "The Nature of Speech, and its Interpretation."

In this research a high-quality telephonic circuit was employed, comprising a condenser transmitter, an artificial line including thermionic amplifiers, an attenuator for weakening the speech currents in a known ratio, wave filters (described presently) for passing currents only within certain ranges of frequency, and received by high-quality magneto receiving telephones. By this apparatus speech sounds could be transmitted without distortion, but with amplitudes increased or diminished in exactly known ratios. When the amplitude is changed in the ratio of $2\cdot71828$ to 1, this is called reduction by 1 *napier*, since the above numeric is the base of the Napierian system of logarithms. If it is reduced in the ratio of $(2\cdot71828)^n$ to 1, this is called reduction by $n$ napiers.

If we begin with a just audible speech sound, which we have seen corresponds to a variable air pressure of about $0\cdot001$ dyne per cm$^2$ (R.M.S. value) for sounds of frequency about 1 000 p.p.s., and if we then increase the amplitude by about 7 napiers, which brings the R.M.S. pressure to about 1 dyne per cm$^2$, since $(2\cdot71828\ldots)^7 = 1\,096$; we shall have a sound the loudness of which corresponds to the maximum articulation as judged by the percentage of correctly heard test-syllables transmitted. If the amplitude is increased still more the articulation falls off again, as shown by the curve in Fig. 2. The ear is "deafened," as we say, by very loud speech. Hence there is a certain amplitude which gives the maximum of telephonic speech articulation or intelligibility. By means of the filters, which are artificial telephone lines constructed with inductive resistances in series of capacities in parallel, or vice versa, it is possible to attenuate very rapidly speech currents of a certain range of frequency either above or below certain selected limits. The results of this filtering on telephonic speech transmission are very remarkable. According to the researches of Harvey Fletcher and those of Crandall and Mackenzie a filter which cuts off all currents of frequency below 500 p.p.s. stops 60 per cent of the speech energy but only 2 per cent of the articulation. This means that the speech is greatly decreased in loudness but not much in clearness or intelligibility. On the other hand, a filter which cuts off all frequencies above 1 500 eliminates only 10 per cent of speech energy but reduces the articulation by 35 per cent. This means that the speech is not much reduced in loudness but is very reduced in clearness. A filter which cuts off all frequencies above 3 000 p.p.s. has as bad an effect on articulation as one which cuts off all below 1 000 p.p.s.

Some speech sounds, such as the vowels u, o and e have characteristics carried by frequencies below 1 000, but the fricative consonants denoted by the letters i, z and th have their specific qualities conveyed by high-frequency harmonics and are greatly affected by cutting off frequencies above 3 000 p.p.s.

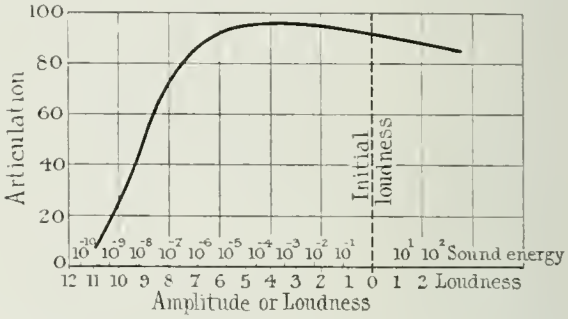


FIG. 2.—Curve showing the "articulation" of a telephone circuit in terms of loudness of the speech (Harvey Fletcher).

The sounds denoted by the letters f, v and th are most difficult to hear and are responsible for 50 per cent of the mistakes of telephonic interpretation. Their current articulation seems to depend on the transmission of harmonics of very high frequency. The general conclusion is that any telephonic apparatus designed for good speech transmission must transmit with equal efficiency and without distortion sounds of all frequencies from 100 to 5 000 p.p.s. Although the greater part of the sound energy is transmitted by currents and air waves of frequencies below 1 000 p.p.s., yet the essential characteristics of speech, and especially of consonant sounds, are conveyed by frequencies much higher than 1 000 p.p.s. and up to 5 000 p.p.s.

The poor transmission over ordinary telephonic circuits of certain consonants such as f, v and th is responsible for much difficulty, especially in the case of the names of digits such as *five*, *nine* and *three* in calling numbers.

(7) In correlation with this part of the subject it would be interesting to discuss theories of hearing, especially the manner in which the ear performs a sort of instantaneous Fourier analysis of complex air-

---

* See *Journal of the Franklin Institute*, June, 1922.

wave forms, appreciating the harmonics present with the fundamental tone, and not only their relative amplitude but, to some extent, their phase differences. Time, however, forbids anything but a brief reference to two well-known theories. There is in the internal chamber of the ear a spiral tube called the cochlea and in this tube is contained an organ called Corti's organ. This comprises a vast number of fibres, some say as many as 16 000. According to a theory put forward by von Helmholtz in 1863, and modified by Gray, Corti's organ may be regarded as a microscopic harp of 10 000 strings each of which is tuned to resonate to a particular rate of vibration. It is therefore supposed to pick out and respond to the impulses due to the corresponding harmonic frequency in a sound wave, just as certain strings of a piano can be set in vibration by a clear note sung into it by a powerful singer. This theory, though widely accepted, has, however, been opposed by some biologists and in particular the late Sir Thomas Wrightson, who propounded another view in 1873 which he elaborated in a book published in 1918 and entitled "The Mechanism of the Internal Ear." In a lecture given at the Royal Institution, London, in March, 1919,* the eminent physiologist, Sir Arthur Keith, expounded this latter theory and explained that by Sir Thomas Wrightson's hypothesis the organ of Corti does not act as a resonator at all, as supposed by Helmholtz, but is an extraordinarily sensitive pressure gauge which registers and appreciates minute and rapid changes of pressure applied to the fluid in the cochlea by the sound waves. It appreciates not only the frequency of these pressure-changes and their amplitude but also the manner in which the pressure alters during a single cycle of operations.

The nerve fibres in the Corti organ convey this information to the brain centres of audition where they are translated into sensations of sound, with its three distinctive qualities of pitch, loudness and quality.

If we call to mind the very distinctive qualities of individual human voices, even when pronouncing the same words, and the manner in which these tones can express emotions, feelings, or personality, all of which must be represented physically by minute differences in wave-form, we realize that the human ear is indeed one of the marvels of creation in its amazing powers.

## V. THE TELEPHONE CONSIDERED AS AN ENERGY-TRANSLATING APPLIANCE.

(8) When we consider the very complicated nature of our vocal or speech organs, as well as the training and practice necessary for their efficient use, and the parts played by the larynx, oral cavity, lips, tongue and teeth in speaking, we find reason for great surprise that the mere vibrations of a small flexible disc such as the iron diaphragm of a Bell receiver can impress upon the air, vibrations of the highly irregular waveform necessary to reproduce speech sounds. When a thin, flexible disc is held firmly at the edges it can only vibrate in certain ways in consequence of elastic stretching, and it has, like a stretched string, a fundamental mode of vibration in which it takes a convex or concave form as a whole and also certain harmonic modes of vibrating in sections. In the case of a circular flexible disc of radius $r$, thickness $t$, made of material of density $d$, Young's modulus $e$ and Poisson ratio $q$, Lord Rayleigh gave * the following formula for the fundamental rate of vibration $n$ of a circular disc clamped all round the edge :—

$$n = \frac{2 \cdot 56 t \sqrt{e}}{\pi r^2 \sqrt{(3d)} \sqrt{(1 - q^2)}} \quad . \quad . \quad . \quad (17)$$

The Poisson ratio $q$ is the ratio of the lateral contraction to longitudinal extension of an elastic material when stretched. Its numerical value for steel is about $0 \cdot 31$, so that $\sqrt{(1 - q^2)}$ is nearly $0 \cdot 95$ or not far from unity. Hence, approximately,

$$n = 1 \cdot 48 \frac{t}{\pi r^2} \sqrt{\left(\frac{e}{d}\right)} \quad . \quad . \quad . \quad . \quad (18)$$

But $\sqrt{(e/d)}$ is the velocity of sound in the material. We have therefore this very simple rule, that the fundamental frequency of vibration of a circular diaphragm clamped all round the edge is nearly equal to $1\frac{1}{2}$ times the ratio of its thickness to its area, multiplied by the velocity of sound in the material.

The diaphragms of Bell receivers are usually made of thin low-hysteretic steel such as that called "Stalloy" containing 2·75 per cent of silicon, and are about 5·0 cm in effective diameter and 0·025 cm thick. The ratio of thickness to area is then 1 : 785.

The velocity of sound in steel is about 4 710 metres per second and hence the natural frequencies of the diaphragm by the above formula should not be far from 942 p.p.s.

For a circular steel diaphragm of thickness $t$ and diameter $d$ cm the above rule approximates to $900\,000\ t/d^2$. Hence for a diaphragm 1/40 cm thick and 5 cm in diameter it gives $n = 900$.

These dimensions have been arrived at by trial and give a frequency not far from 800 p.p.s., which is generally taken as a kind of mean frequency for speech waves.

(9) In a paper † published in 1912 by A. E. Kennelly and G. W. Pierce, it was shown that there are four constants of a telephone receiver which determine its performance throughout the frequency range of ordinary telephony, viz. 100 to 2 500 p.p.s. These are : (1) The *force-factor* ($A$) or electromagnetic pull on the diaphragm in dynes per absolute C.G.S. unit of current in the coils ; (2) the *equivalent mass* ($m$) of the diaphragm or a mass which, moving with the velocity of the centre of the diaphragm, has the same kinetic energy as the whole diaphragm ; (3) the *motional resistance* ($r$) of the diaphragm, in dynes per unit of velocity referred to the motion of the equivalent mass ; and (4) the *stiffness constant* ($s$) or force in dynes per unit displacement in cm opposing the movement of the diaphragm and referred to the equivalent mass at the centre.

---

* See *Proceedings of the Royal Institute of Great Britain*, 1919, vol. 22, part 3, p. 508.

* See "Treatise on Sound," vol. 1, 2nd ed., p. 367.

† See *Proceedings of the American Academy of Arts and Sciences*, 1912, vol. 48, p. 113.

In the above-mentioned paper Kennelly and Pierce showed that valuable help could be derived in determining these receiver constants from a diagram called the *motional impedance circle* of the instrument.

If we measure with a suitable bridge arrangement the resistance and reactance of the telephone coils with alternating current of known frequency and pure sine wave-form, both when the diaphragm is freely vibrating and also when it is held fixed or damped, we find differences between these free and fixed values which are called respectively the *motional resistance* and *motional reactance.*

If we plot the above differences as ordinates in terms of the angular velocity of the current or of $2\pi$ times the frequency $= 2\pi n = \omega$, we obtain curves as shown in Fig. 3. The motional resistance rises with the frequency to a maximum and then falls quickly through zero to a negative maximum. The motional reactance is mostly negative and has a maximum nearly coinciding with the resonance frequency of the diaphragm, at which frequency the power absorption of the receiver is a maximum also.

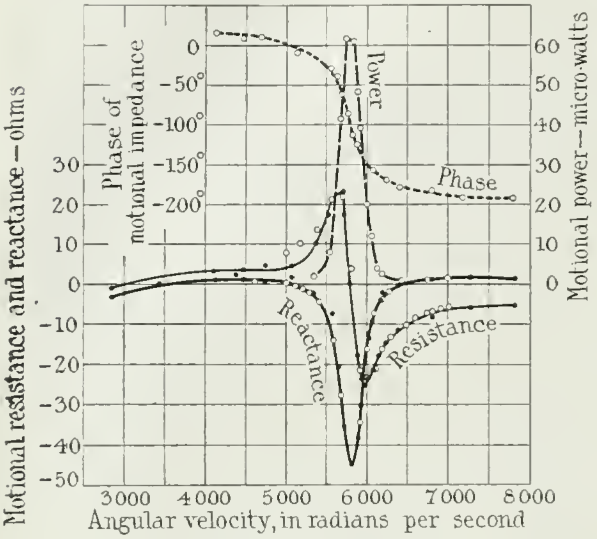


Fig. 3.—Curves showing the motional resistance, reactance, and power for a Bell telephone receiver, plotted in terms of angular velocity or $2\pi$ times the frequency (Kennelly and Pierce).

If we plot the motional resistance horizontally as abscissæ and the motional reactance vertically as ordinates, we obtain as graph a circle called the *motional impedance circle*, and this passes through the origin. The diameter of this circle is depressed below the horizontal by an angle called the *depression angle* (see Fig. 4). The chords of this circle drawn through the origin give the vector impedance of the telephone for the corresponding frequency. The diameter of this circle drawn through the origin gives the motional impedance of the telephone at resonance. It was pointed out by Kennelly and Pierce in 1912 that from an inspection of this motional impedance circle it is possible to obtain data which assist in giving the value of the four principal constants when combined with one other measurement. Kennelly and Affel showed * in 1915 that if we measure the amplitude of vibration of the diaphragm at its centre, produced by a sinusoidal alternating current through the coils of the telephone, we can find by the aid of this measurement and the motional impedance circle all four characteristic quantities of the receiver.

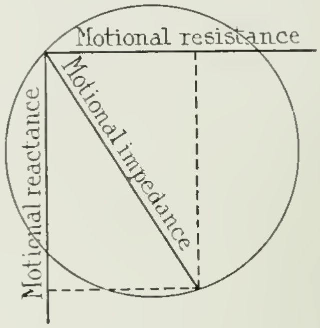


Fig. 4.—Motional impedance circle of a Bell telephone receiver (Kennelly and Pierce).

Kennelly and Affel devised an ingenious optical instrument for making measurements of the amplitude of motion of the telephone diaphragm, not only at the centre but at any point on it.

A. E. Kennelly and H. O. Taylor have given a curve (Report on Experimental Investigation read before the *American Philosophical Society*, April 22, 1915), showing that when a certain Bell receiver was traversed by an alternating current of 2 milliamperes with frequency considerably removed (say by 20 per cent or more) from the resonance frequency of the diaphragm, the amplitude of motion of its centre was found to be about 0·5 micron—that is, 1/20 000 cm or less. This is about equal to the length of the wave of light in

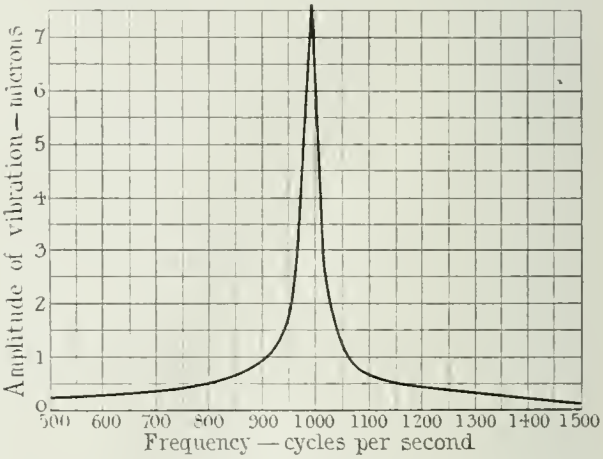


Fig. 5.—Curve showing the amplitude of displacement of the centre of the diaphragm of a certain Bell telephone receiver for various frequencies when an alternating current of 2 milliamperes is passed through the coils (Kennelly and Taylor).

---

* *Proceedings of the American Academy of Arts and Sciences*, 1915, vol. 51, p. 421.

the middle of the visible spectrum, viz. about 5 000 Å.U. If the frequency is gradually brought up to the resonance frequency of the diaphragm, the amplitude of motion would be increased 15 or 20 times, say to 7 to 10 microns as shown in Fig. 5. Lord Rayleigh found for a certain receiver that the amplitude of motion of the diaphragm when producing a just audible sound of frequency 256 was $6 \cdot 8 \times 10^{-8}$ cm, or only about 7 Å.U.

P. E. Shaw,* by the use of an electric micrometer of his own invention, found, in very close agreement with Lord Rayleigh, that the amplitude of motion of the diaphragm of a telephone for a just audible impulsive sound, was $7 \times 10^{-8}$ cm, or 7 Å.U.

Taking the amplitude of the air particle for the just audible sound to an expectant ear to be unity, he found that the amplitude for a non-expectant ear must be increased to 7 or even 70, for a very loud sound to 1 400, and for an overpowering sound to 7 000.

Thus it appears that the amplitude of motion of the air particle near the mouth of a speaker in a conversational tone is about 100 Å.U. or 1/100 000 mm, and the amplitude of motion of the centre of a telephone diaphragm when producing a speech sound just comfortably heard by a normal ear is about 1/20 000 mm. The amplitude of motion of the air particle near the diaphragm is therefore considerably less than that of the diaphragm itself at the centre.

(10) In connection with this part of the subject an important matter is the displacement of the diaphragm at various distances from the centre; in other words, the shape of the diaphragm as it vibrates.

A. E. Kennelly and H. O. Taylor have applied the above special form of optical callipers to this investigation and have given curves in a paper read before the American Philosophical Society in April, 1915, on "Explorations over the Vibrating Surfaces of Telephonic Diaphragms" representing the principal section of the vibrating diaphragm. They have investigated the matter theoretically and compared the results of observations and the predictions of theory. The exact theoretical prediction of the shape of a circular vibrating diaphragm when clamped at the edges requires rather advanced mathematics. I find, however, that a simple empirical formula agrees very well with experimental results. If $r$ is the radius of a circular telephone diaphragm, and if $y$ is the maximum displacement from a flat zero surface of a point on the diaphragm at a radial distance $x$ from the centre, and if $Y$ is the maximum displacement at the centre of the diaphragm, then :—

$$y = Y \cos^2\left(\frac{\pi}{2} \cdot \frac{x}{r}\right) \quad . \quad . \quad . \quad (19)$$

Thus, if $x = 0$ then $y = Y$, and if $x = r$ then $y = 0$, which agrees with the boundary conditions. Suppose we consider the diaphragm in its normal position to be flat and then to be drawn inwards in the centre so that the profile of its principal section is the curve whose equation is given above. The displacements at various radial distances will agree fairly well with the measurements made by Kennelly and Taylor.

If $V$ is the volume displacement of the air in front of the diaphragm due to this movement from flat to concave, then it is clear that :—

$$V = 2\pi\int_0^r x \,.\, Y \cos^2\left(\frac{\pi}{2} \cdot \frac{x}{r}\right) dx = \pi r^2 Y\left(\frac{1}{2} - \frac{2}{\pi^2}\right) \quad (20)$$

But $\pi r^2 = a$ is the whole area of the diaphragm, and $Y$ is the displacement at the centre. If we consider a right circular cylinder whose height is $Y$ and the area of whose base is $\beta$, then to have the same volume $V$ it is obvious that :—

$$\frac{\beta}{a} = \left(\frac{1}{2} - \frac{2}{\pi^2}\right) = 0 \cdot 29 \quad . \quad . \quad . \quad (21)$$

We may then say that the effective area of a circular telephone diaphragm is $0 \cdot 29$ of its actual area. The *effective area* is defined as the area which, if equally displaced at all points with the displacement of the centre of the real diaphragm, gives an equal volume displacement to the air. For a diaphragm 5 cm in diameter the effective area is $5 \cdot 8$ cm$^2$.

(11) If we consider a small source of sound radiating equally in all directions, and if we describe around it a sphere of radius $r$ small compared with the wave-length $\lambda$, then at each oscillation a certain maximum volume of air, $V$, is displaced outwards and inwards by the wave motion across this spherical surface. If the frequency is $n$ then it is proved in Appendix I that the total energy in ergs per second ($W$) conveyed from the source by the sound waves is given by the equation :—

$$W = \frac{n^4 V^2}{400\,000} \text{ ergs} \quad . \quad . \quad . \quad (22)$$

where $V$ is measured in cubic centimetres. The above formula holds good approximately for an ordinary telephone receiver, provided we write for $V$ the product $Y\beta$, where $Y$ is the maximum displacement of the centre of the diaphragm in centimetres, and $\beta$ is the effective area of the diaphragm in square centimetres. If then the telephone coils are traversed by a current $I$ reckoned in milliamperes and have an effective or high-frequency resistance $R$ ohms, the power $P$ dissipated as heat by the telephone is $10\, I^2 R$ ergs. The power given off in sound-wave energy per second is given by

$$\frac{n^4 Y^2 \beta^2}{4 \times 10^5} \text{ ergs}$$

or if $Y$ is measured in microns ($\mu$) * then the sound power radiated is :—

$$\frac{n^4 Y^2 \beta^2}{4 \times 10^{13}} \text{ ergs} \quad . \quad . \quad . \quad . \quad . \quad (23)$$

Since this radiated power is small compared with $P$ the telephone-acoustic efficiency $\eta$ is approximately given by :—

$$\eta = \frac{n^4 Y^2 \beta^2}{4 \times 10^{14} I^2 R} \quad . \quad . \quad . \quad . \quad (24)$$

---

* See *Proceedings of the Royal Society*, 1905, vol. 76 A, p. 360.

* $\mu = 10^{-4}$ cm.

For a telephone receiver with the usual 5 cm diameter diaphragm, $\beta = 5\cdot 8$ cm², and the acoustic efficiency is then :—

$$\eta = \frac{8\cdot 4}{10^{14}} \cdot \frac{n^4 Y^2}{I^2 R} \quad . \quad . \quad . \quad . \quad (25)$$

Kennelly and Affel have given a number of data * of a certain Bell bipole receiver with the standard diaphragm, to which the above formula can be applied. At the resonance frequency ($n = 1\,020$) of this telephone, the diaphragm displacement ($Y$) at the centre was 10·45 microns, the effective resistance $R$ was 224 ohms and the current 2 mA.

With the above values we obtain an efficiency $\eta = 0\cdot 011$, or a little over 1 per cent. Taking from other data given by the above authors for the same telephone at a frequency $n = 1\,000$, slightly removed from resonance when $Y = 8\cdot 23\,\mu$ and $R = 283$ ohms, we obtain $\eta = 0\cdot 005$, or $\frac{1}{2}$ per cent efficiency. At a frequency $n = 702$, far removed from resonance, we find $Y = 1\cdot 8\,\mu$ and $R = 130$, which gives $\eta = 0\cdot 00013$, or an efficiency of less than 1/80th of 1 per cent.

At the standard frequency $n = 800$ at which $Y = 1\cdot 9\,\mu$ and $R = 166$ ohms the efficiency is just $0\cdot 00018$, or rather less than 1/50th of 1 per cent.

Speaking very roughly we might say that a Bell telephone receiver used in ordinary telephonic conversation is taking in power electrically about equal to 1 milliwatt, and is giving out power in the form of speech air-waves about equal to 1 microwatt. It is an extremely inefficient machine for the transformation of energy, and far from perfect in its articulation as a speech-producing appliance. The inefficiency of the Bell telephone was pointed out many years ago by H. Abraham,† who deduced from certain measurements an acoustic efficiency of 1 part in 700 for a certain receiver at a frequency of 200 and a current of about 3·3 mA.

Louis V. King, in an article in *The Year Book of Wireless Telegraphy* for 1919, made deductions from some of the measurements of Kennelly and Taylor, which agree substantially with those of the author respecting the acoustic efficiency of the magneto receiver.

Here, then, is the chief unsolved problem of modern telephony, viz. the invention of a receiver acoustically more efficient than the present type of magneto receiver, and with equal or better speech-reproducing power.

The chief sources of the inefficiency of the magneto telephone receiver are :—

(1) Joulean heat loss in the coil ;

(2) Eddy-current losses in the diaphragm and pole-pieces ;

(3) Magnetic hysteresis losses in the same ;

(4) Mechanical work done in bending the iron diaphragm ; and

(5) Vortex motion or frictional losses due to air movements which do not contribute to wave production.

Whilst considerable improvements have been effected it is difficult to see how any great improvement in efficiency can take place without radical departure from the fundamental principles of Bell's invention. In the well-known telephones of S. G. Brown the iron diaphragm of the Bell receiver is replaced by a steel reed tuned to a certain frequency. The magnetic pull of the permanent part of the field magnets takes effect on this reed, which is capable of adjustment. To the reed is attached an aluminium cone with a flexible rim which plays the part of the diaphragm. This diaphragm only partakes of these movements of the reed which are due to the telephone currents, so that when no speech currents are being received there is no strain on the diaphragm. Also, by reason of the material being aluminium, magnetic losses are absent. No doubt this type of receiver possesses a somewhat higher acoustic efficiency than the Bell, but I have not been able to find any determinations of it by independent observers.

Apart from the energy losses in the telephone, another defect from one point of view is that its diaphragm has such a marked resonance for a frequency lying in the middle range of the voice. The amplitude of vibration is greatly increased at this resonance frequency and hence speech distortion occurs. In the human ear the tympanum is small and has a very high natural frequency. The result is that it can respond to those high harmonics which, as we have seen, give quality to the sound, especially consonantal speech sounds. Having regard to the enormous public use of the telephone, not only in ordinary telephony but in radio-telephony where the available power is limited, the improvement of the acoustic efficiency of the receiver is one of the most important problems that can engage scientific attention. As it stands, the telephone receiver is by far the most inefficient of all our electrical energy-transforming devices.

(11) The only forms of practical receiver for telephony which have so far presented themselves as just possible alternatives to the electromagnetic or Bell type are those depending (i) upon thermal actions, (ii) on electrostatic attractions, and (iii) upon variations in the friction or adhesion of certain materials, produced by the action of small currents or differences of potential.

An example of a thermal receiver is that of MM. de Lange and Fischer which was described in a paper sent to the Royal Society in 1915.* It consists of a loop of very fine platinum wire or very thin strip of gold or platinum enclosed in a tube or capsule with exit holes. When telephonic speech currents are sent through the wire it is heated and the sudden expansion of the surrounding air generates sound waves which make their exit from the holes. This chamber may take the form of an ebonite capsule which is placed in the external orifice of the ear. This appliance has been much studied in the United States as a precision source of sound. H. D. Arnold and I. B. Crandall have obtained mathematical expressions connecting the heating current and air pressure-changes for certain forms of the instrument.† Another theoretical paper has lately been published on it by E. C. Wente.*

---

* See A. E. KENNELLY and H. A. AFFEL : "The Mechanics of Telephone Receiver Diaphragms as Derived from their Motional Impedance Circles," *Proceedings of the American Academy of Arts and Sciences*, 1915, vol. 51, p. 428, Table 1.

† See *Comptes Rendus*, 1907, vol. 144, p. 906.

* See *Proceedings of the Royal Society*, 1915, vol. 91 A, p. 239.

† See *Physical Review*, 1917, vol. 10, p. 22.

Although this thermophone is of service in the research laboratory it has not yet replaced in any way the Bell magneto-receiver in practice.

Another type of thermal receiver of some promise is that due to Mr. Leslie Miller, which he calls a loose-contact thermal receiver.† In this receiver two pieces of certain substances are employed, one in the form of a small disc attached to the back of an aluminium diaphragm, and the other in the form of a ball or point just slightly pressed in contact with the disc. The substances may be galena and carbon (graphite), or both carbon. A small direct current is passed across the contact and, when a telephonic speech current is superimposed, the diaphragm reproduces acoustically the speech. The action may be due to a slight separation between the contact points due to the repulsion between the elements of a conductor conveying a direct electric current, and this is increased or diminished when the alternating speech current is superimposed, thus causing the diaphragm to vibrate. This principle of a loose microphonic contact as a speech reproducer is well worth continued investigation. We have then in the next place the electrostatic receiver which in a certain form was originally suggested by Dolbear and by Edison, but in its most perfect form is the condenser transmitter and receiver already described.

Lastly we may mention the variable-friction principle which was employed by Edison in the quite early days of telephony in his chalk cylinder receiver.

In this instrument a cylinder of chalk, which Edison found it best to moisten with a solution of hydrodisodic phosphate, is slowly revolved. On it rests a light metal bar in connection with a mica diaphragm. When the cylinder revolves the slight friction displaces the bar and cups in the diaphragm, but when a telephonic current passes from the metal to the chalk the friction is reduced and the bar slips and communicates its motion to the diaphragm. Sir William Barrett investigated the effect in 1879 and 1880 ‡ and stated that he found that if the chalk was dry there was an increase of friction. Mr. Rollo Appleyard described in 1905 the adhesion of a metal plate to a dielectric when a difference of potential is made between them.

This fact was re-discovered and applied in the construction of a telephone receiver by Messrs. K. Rahbek and A. Johnsen using an agate cylinder and a metal contact block, as described in a Lecture given before this Institution on 26th May, 1921. The most general statement that can be made is that when two substances, one or both of which may be a metal, or in a few cases both non-metals, are in contact with each other, the sliding friction is either reduced or increased by the creation of a difference of potential between them.

The whole phenomena has during the last two years been very carefully re-examined in the electrical research laboratory at University College, London, by Mr. H. M. Barlow, and the results of his work will before long be made known. In all these methods there are possibilities of constructing a telephone receiver which may perhaps be found to have greater acoustic efficiency than the present types of Bell receiver.

An electrodynamic receiver which seems to have great possibilities in the way of improved efficiency has been invented by M. L. Gaumont, who exhibited it recently to the Academy of Sciences at Paris. The vibrating part of the instrument consists of a little cone of silk wound with a spiral of aluminium wire through which the telephonic currents flow. This is fixed between the poles of an electromagnet or of a powerful permanent magnet the poles of which are bored out with holes to permit the air waves, which are produced when the coil vibrates in the magnetic field, to pass. This receiver is said to emit a very loud and clear sound.

The energy-transforming efficiency of the microphone transmitter has not been made the subject of so much experimental investigation as that of the Bell receiver.

In the ordinary microphone transmitter with associated induction coil we supply power in two forms, (i) in the form of direct current, and (ii) in the form of aerial speech wave power which vibrates the diaphragm and modulates the direct current. We have therefore joulean losses in the carbon granules and in the induction coil circuits as well as magnetic energy losses in the latter, and, in addition, work is spent in the deflection of the diaphragm and in creating eddy currents in the air near it. Owing to the necessity for supplying the direct-current power, the actual proportion of the whole power applied which makes its appearance as electric speech current-power in the line must be small, but I have not been able to obtain actually measured results.

To overcome the difficulties connected with the low resonance frequency of the ordinary carbon microphone diaphragm, there has been a certain use of the condenser transmitter with a very tightly strained and therefore more aperiodic diaphragm for certain purposes such as wireless telephone broadcasting. Also improved forms of magneto telephone with thick diaphragms which have a natural frequency above the ordinary speech range have been employed very successfully for the same purpose in Great Britain. It would, however, be very advantageous to get rid entirely of the necessity for a diaphragm. It is well known that the carbon electric arc can be used as a speech transmitter. Hence the new glow discharge microphone of Dr. Phillips Thomas of the Westinghouse Electric Company of America, in which the speech air waves directly modulate an electric discharge current, is a distinct advance and is said to have been used for some time with marked success as a broadcasting transmitter in the United States.

## VI. THE TRANSMISSION PROBLEMS OF THE TELEPHONE LINE.

(12) When we turn from the consideration of the telephone transmitter and receiver to that of the tele-

---

* See *Physical Review*, 1922, vol. 19, p. 333.

† See *Journal of the Wireless Society of London*, 1921, vol. 2, p. 141.

‡ See *Nature*, 18th March, 1880.

phone line we find a number of interesting problems to which a fairly satisfactory solution has been given of late years. In the young days of telephony it was not at all clearly understood that the inductance of the line plays a more important part in telephony than it does, or at least did, in submarine cable telegraphy.

Hence the early telephonists applied the theory worked out by Lord Kelvin for the submarine cable transmitting relatively low-frequency currents to the telephone cable transmitting high-frequency currents, with the result that erroneous ideas became prevalent.

We owe to Mr. Oliver Heaviside, as is now everywhere acknowledged, the enunciation of the true theory of the telephone line and an explanation in 1887 of the causes of, and best remedy for, the distortion of the wave-form of the speech currents it produces. The various harmonic currents into which the complicated electric speech waves can be resolved travel at different speeds along the cable and attenuate at different rates. The short waves travel faster and attenuate more rapidly than the longer electric waves. Hence a distortion of the wave-form results, and beyond a certain length of line the reproduced articulate sound becomes unrecognizable by the ear. Heaviside gave the statement of the conditions which must be fulfilled by a distortionless cable, and insisted on the necessity for increasing its inductance to approximate to this condition in the case of existing lines.

The late Professor S. P. Thompson in 1891 and 1893 described in British Patent Specifications various remedies for distortion, and in 1893 read a paper at Chicago on "Ocean Telephony," which drew much attention to the subject. In his Presidential Address to this Institution in 1899 he strongly urged a practical trial of his suggestions.

As a long telephone cable is a somewhat expensive article, practical telephonists were obliged to advance slowly. The introduction of the dry-core or dry loose-paper insulation in a lead sheath, in or about the year 1887, aided in the reduction of cable capacity and was therefore a step in the right direction.

The important papers published in 1899 and 1900 by M. I. Pupin brought within the scope of practical achievement the scientific recommendations of Heaviside as to the increase of inductance of the line. Pupin showed theoretically and practically that a telephone line can have its inductance increased so as to approximate to the Heaviside condition for non-distortion by the insertion of special inductance coils at equispaced intervals. If these intervals are not much greater than one-tenth of the wave-length of the electric wave travelling on the so-loaded cable, the coils act as if their inductance were uniformly distributed along the line.

If the impedance per unit length of the line changes suddenly at any point to a higher or lower value, then a wave of electric current travelling along the line suffers partial reflection and partial transmission at that junction exactly as a ray of light is partly reflected and partly transmitted at the bounding surface of two transparent media of different refractive index, provided that the change in refractive index is very sudden. In short, the quantity we call the characteristic impedance of a telephone line, which in complex expression is $\sqrt{(R + jwL)}/\sqrt{(S + jwC)}$ where $R$, $L$, $S$ and $C$ are the resistance, inductance, leakance and capacity of the line per mile or naut, is exactly analogous to the quantity called the refractive index in the case of light propagation.

If, then, a telephone line has an inductance coil inserted at some point, there is a partial reflection of the electric waves travelling along the line at that point. If coils are spaced apart at distances large compared with the wave-length the repeated reflections would render the line non-transmissive. If, however, the coils are at intervals short compared with the wave-length, then they are equivalent to a uniform distribution of added inductance along the line and diminish its attenuation.

A quantity of fundamental importance in the case of a telephone line is its *attenuation length* or the product of its attenuation constant and its length in miles. The attenuation constant may be defined as the reciprocal of the length of the line in which the current or voltage falls in the ratio of 2·71828 to 1 or to 36·7 per cent of its initial value, or by 1 napier. Telephonists express the attenuating qualities of any line in terms of those of a certain standard cable consisting of a copper core weighing 20 lb. to the mile, one mile of double core, lead and return, having a resistance of 88 ohms, an inductance of 1 millihenry, and a line-to-line capacity of 0·05 microfarad. This standard cable has an attenuation of about 0·1 per mile, which means that in 10 miles' length the current or voltage drops in the ratio of 2·71828 . . . to 1, or by 1 napier. The extreme limit of telephonic speech with simple present-day carbon transmitter, induction coil and Bell receiver is about 40 or 45 miles of standard cable and for good speech about 25 miles. The attenuation of any other cable is now commonly expressed in its equivalent in miles of standard cable (M.S.C.). Owing to losses in subscribers' circuits and in the exchange connections the total attenuation in a long trunk line should not exceed that of 15 or 20 M.S.C.

Pupin's important contribution to the subject of the inductive loading of cables consisted in the proof he gave that the added inductance could be inserted in the form of inductance or loading coils spaced at equal intervals in the line, provided these coil intervals were not more than about one-tenth of the mean wave-length of the speech electric-current waves on the so-loaded cable. Aerial lines and cables began to be loaded in this fashion soon after 1900, with the result that the normal speech range was extended. It is possible to load with coils so as to increase the line inductance from 10 to 250 times that of the unloaded line. Considerable research has, however, been necessary to find the best form of loading coil. Those first used consisted of a ring-shaped iron core formed of fine iron wire, overwound with two circuits of insulated copper wire for the lead and return circuits so wound as to produce a poleless circular magnetization in the core. In such a wire core the alternating telephonic currents dissipate energy as eddy current and hysteresis loss, and this is equivalent to an increase in the effective resistance of the coils. The problem then was to find a method of making an iron ring in which eddy-current loss should be nearly absent and hysteresis loss small, but permeability sufficiently large to give the required inductance to the coil. The problem was solved by the Western Electric Company of America after great research. These iron cores (called "dust cores") are now made as follows :—

Electrolytically deposited iron is ground up into a powder and the iron grains are coated with zinc dust. The particles are then mixed with shellac as a cement and compressed under 100 tons per square inch into flat rings, which are piled one on the other to make the loading-coil core. This material when subjected to an alternating magnetic force of a frequency 100 to 2 500 p.p.s. has an average magnetic permeability of 34 to 50 when the magnetic flux density is only about 2 C.G.S. lines per $cm^2$. The electric conductivity is extremely small (about 1/80 000th part of that of solid iron) so that eddy-current loss is absent, and hysteresis loss is also very small. The details of one type of loading coil with dust core are as follows : Inductance at 800 p.p.s. and 1 mA = 0·177 H. Effective resistance 9·2 ohms. The core composed of 7 dust rings has a cross-section of 8·3 $cm^2$ and 24·9 cm mean length. Mean permeability at a magnetizing force of 0·0564 = 34. The total turns of wire on the ring are 1 120 put on in 4 separate sections on the 4 quadrants, and two such coils in series are inserted in the lead and return of the telephone circuit.

In the case of underground cables it is customary to space the loading coils about 2 to 2·5 miles apart and to give them such inductance as to add about 55 mH per mile run of the cable. The ratio $R'/L$ for each coil is about 50. Lighter or heavier loading is, however, often employed.

For these loaded lines the attenuation constant ($\alpha$) can easily be proved to be given by the expression $\alpha = \frac{1}{2}[(R/L) + (S/C)]\sqrt{(CL)}$, where $R$ and $L$ denote the total effective resistance and inductance of the line per mile of loop, and $S$ and $C$ the leakance and capacity. It is seen, therefore, that the insulation resistance of the loading coil, as well as that of the line, must be very high if the effect of the added inductance is not to be nullified by the leakance.

In aerial telephone lines the loading coils are placed from 8 to 12 miles apart and have each an inductance of about 0·25 H or less, so as to give the line a total inductance of about 40 mH or so per mile of loop. The coils are put in iron boxes attached to the telegraph posts. In aerial lines one difficulty of securing the full advantage of loading is the ever-varying leakance of the line.* The longest aerial loaded telephone line in the world is the New York–San Francisco–Los Angeles line of the American Telephone and Telegraph Company, which is 3 790 miles in length and was completed in 1916. It is loaded every 8 miles with coils having an inductance of 0·25 H and 6·5 ohms effective resistance, giving the line an average inductance of 37 mH per loop mile. This reduces the attenuation constant to 0·00125. The electric wave therefore runs 800 miles before its amplitude is reduced to 36·7 per cent of its initial value, or by 1 napier. Another long aerial loaded line is the Berlin–Rome line, 1 300 miles in length, in which loading coils are inserted every 10 km or 6¼ miles, each coil having an inductance of 0·2 H, thus raising the average inductance of the line to 22 mH per loop kilometre and reducing the attenuation to 0·0011 per kilometre of loop.

(13) It was a more difficult problem to load with coils a submarine cable, but this was successfully accomplished by Messrs. Siemens Bros. in the English Channel telephone cable laid by the British Post Office in 1910. The details were described in a valuable paper read before this Institution in 1910 by Lt.-Colonel W. A. J. O'Meara, at that time Engineer-in-Chief to the British Post Office.*

Inductance coils of special construction were designed for enclosure within the gutta-percha insulation and armouring of the cable, the coils having an inductance of 0·1 H at 750 p.p.s. and being placed at intervals of 1 naut (= 1·153 miles).

The insertion of the coils required an increase in the diameter of the finished cable at intervals of 1 naut, but it was not too great to permit the cable being handled and laid in the relatively shallow water of the Channel.

Similar coil-loaded cables were laid to Belgium in 1911 and under the Irish Channel in 1913 by the British Post Office. The difficulties involved in the construction, laying, and especially in the raising and repairing of such coil-loaded submarine cables, would be far too great in the case of deep-sea cables to render them practical, and hence much attention has been directed to the alternative method of loading called uniform loading, which was first practically employed in 1902 by the Danish telephone engineer C. E. Krarup in a telephone cable laid between Elsinore and Helsingborg.

The method consists in overwinding or whipping the copper conductor with one or two layers of soft iron wire put on in close turns. This increases the inductance of the core and also to some extent its capacity and effective resistance.

It is not found practicable to increase the layers of iron wire so as to give an added inductance per mile equal to that which can be obtained by coil loading, without passing the point of minimum attenuation constant, owing to the simultaneous increase of the capacity and resistance. A certain compromise can be effected by somewhat increasing the diameter of the stranded copper core as compared with that which would be employed if the cable were to be coil-loaded instead of uniformly loaded.

In the case of uniformly loaded cables there is more difficulty in the predetermination of the resulting improvement in reduction of the attenuation constant by the loading, owing to the uncertainty which must exist as to the exact value to be ascribed to the magnetic permeability of the iron under the conditions in which it is used. When employing coil loading we can always make fairly exact measurements of the effective resistance and inductance of a sample loading coil, and if the cable is a double parallel-wire cable of known inductance, capacity and resistance per mile, we can then predict with very approximate accuracy the effect of loading at certain intervals the said cable with the measured type of coil. In the uniformly loaded cable we have in the iron wire spiral an imperfectly complete iron path for the lines of magnetic flux. The magnetizing forces are weak, owing to the small value of the telephonic currents, and the frequency and force are constantly varying within wide limits. Nevertheless, experience has shown that if we ascribe to the iron a mean permeability of 110 or 115 the predicted inductance agrees fairly well with the measured values of that of the uniformly loaded cable. In addition to several short telephone cables of this type laid in North Sea waters prior to 1904, an Anglo-French cable was laid across the English Channel in 1912 by the French Government, the cable being made and laid by the Telegraph Construction and Maintenance Co. of London. This cable is a four-core cable, each core consisting of copper conductors weighing 300 lb. per naut. Each core is whipped with one layer of iron wire 0·012 inch in diameter, and four such whipped cores are made up into a double-circuit quad cable. The wire-to-wire capacity is 0·176 $\mu$F per naut of loop and at a frequency of 1 000 the attenuation is 0·018 per naut. In the case of the coil-loaded 1910 cable the attenuation at 1 000 p.p.s. is 0·020 but the copper core of the last-named cable weighs only 160 lb. per naut. Hence it is seen that by nearly doubling the section of copper core the iron wire single-layer whipping produces the same effect as the coil-loading as regards attenuation.

---

* Valuable information on this subject was given in 1914 by Mr. J. G. Hill, of the General Post Office, in a paper on "The Loading of Aerial Lines and the Constants of Loaded Circuits" (see *Electrician*, 1914, vol. 62, p. 602) which was read before the Institution of Post Office Electrical Engineers.

* See *Journal I.E.E.*, 1911, vol. 46, p. 309.

One of the latest examples of this type of uniformly loaded telephone cable is that laid in triplicate between Key West on the coast of Florida, U.S.A., and Havana, on the island of Cuba, a distance of 105 nautical miles (1 nautical mile = 6 087 feet). Since the sea channel has a maximum depth of 1 000 fathoms in the Florida Straits, no type of cable except the standard deep-sea type with G.P. insulation was possible. Also it was decided that no type of coil-loaded cable was feasible. Neither was a multiple-circuit cable considered suitable. Hence the only practicable type was an armoured, uniformly loaded cable with a single copper core. In the case, however, of such a cable the return circuit is partly by sea and partly by the armour, and, as the distribution of the return current depends upon the frequency, this, in turn, affects the inductance. It was therefore decided to provide a definite return path by overwinding the insulated copper core with a triple spiral of thin copper tape. The cable was then armoured over this in the usual way. The final effect was to produce a concentric conductor with the central member whipped with fine iron wire 0·008 inch in diameter put on in 120 close turns per inch run. The copper core weighed 350 lb. to the naut and had a resistance of 3·52 ohms at 75° F.

The measured inductance at 1 000 p.p.s. was 4·35 mH and the capacity 0·31 $\mu$F per nautical mile. The attenuation and resistance per naut increase rapidly with the frequency, as shown in the table below.

*Key West–Havana Submarine Uniformly Loaded Telephone Cable,* 105 *Nauts.**

| Frequency, p.p.s. | Attenuation per naut | Resistance, in ohms per naut | Transmission Equivalent, in M.S.C. |
|---|---|---|---|
| 200 | 0·0168 | 4·1 | 19·8 |
| 500 | 0·0194 | 4·5 | 19·4 |
| 1 000 | 0·0216 | 4·8 | 20·8 |
| 2 000 | 0·0278 | 5·8 | 27·2 |
| 3 000 | 0·0363 | 7·2 | 35·7 |
| 4 000 | 0·0460 | 8·7 | 46·0 |
| 5 000 | 0·0575 | 10·7 | 58·0 |
| 6 000 | 0·0725 | 13·7 | 72·7 |

* The above figures are taken from the paper by Messrs. G. A. Abderegg and B. W. Kendall describing this cable, and presented to the Midwinter Convention of the American Institute of Electrical Engineers, New York, February, 1922.

Three separate cables of the above type were made and laid in contiguity in the Florida Straits in 1921. They were manufactured and laid by the Telegraph Construction and Maintenance Company of London for the American Telephone and Telegraph Company, U.S.A.

We may then say that the problem of loading a deep-sea cable has been fairly well solved, and although we cannot nearly approach to the Heaviside condition for distortionless transmission, viz. $LS = CR$, where $L$ = inductance, $S$ = conductance, $C$ = capacity and $R$ = resistance per naut, we can make a very useful approximation to it. Thus in the case of the Key West–Havana cable we have the following actual measured values of the above quantities at 1 000 p.p.s. :—

$$L = 4{\cdot}35 \times 10^{-3}\ \text{H} \qquad S = 12{\cdot}8 \times 10^{-6}\ \text{mho}$$
$$C = 0{\cdot}315 \times 10^{-6}\ \text{F} \quad \text{and} \quad R = 3{\cdot}32\ \text{ohms}$$

Now $LS = 55{\cdot}7 \times 10^{-9}$ and $CR = 1{\cdot}04 \times 10^{-6}$, hence the inductance would have to be increased nearly 20-fold to about 80 mH per naut to fulfil the Heaviside condition for distortionless transmission. Nevertheless we can say that, starting with Heaviside's original suggestion, the successive improvements in loading due to Pupin and Krarup, as put into practice and improved by the careful research of great technical organizations and by the public or Governmental telephone services, have resulted in an extension of the practical telephonic ranges up to, say, 2 000 or perhaps 3 000 miles by aerial lines, 500 miles on underground and 200 miles on submarine cables by suitable loading, as compared with about one-half or one-third of the above distances for unloaded lines of the same type and size.

## VII. The Problem of the Telephone Repeater.

(14) An additional great extension of the practical telephonic range beyond that due to loading the line has been secured by the invention of the simple yet highly effective thermionic telephone repeater. The invention of a satisfactory telephone relay or repeater has occupied the attention of inventors from the earliest days of telephony, and abilities of the highest order have been brought to bear upon it.

A large number of relays or repeaters have been devised which depend upon microphonic contacts or electromagnetic actions, such as those of H. E. Shreve, S. G. Brown, M. I. Pupin, G. A. Campbell, J. Lyons and countless others. It is unnecessary to enter into descriptions of these types of repeaters, because the subsequent invention and development of the more perfect thermionic repeater has for many reasons placed them in a secondary position. The evolution of the thermionic repeater started with the invention by me in 1904 of the oscillation valve or thermionic rectifier for high-frequency currents, consisting of a carbon-filament incandescent lamp having a metal cylinder surrounding the filament carried on a leading-in wire sealed through the bulb. The vacuum was specified to be, and made to be, as high as possible.* When the filament is incandescent the space between it and the cylinder has a unilateral conductivity, and an electron current flows from the filament to the plate under an external impressed E.M.F., provided the filament is made the negative electrode and the cylinder the anode. I gave in the original Royal Society † paper describing this rectifier a diagram of curves which showed the manner in which the current flowing from the filament to the cylinder, now called the *plate current* or *thermionic current*, varied with the potential difference of the filament and cylinder, now called the *plate voltage*. This appliance was used by me as a rectifier for the high-frequency currents employed in wireless telegraphy. I always contemplated and explained its operation as due to the emission of electrons from the incandescent filament, and in my specification insisted on the importance of a very high vacuum to avoid secondary ionization. As far as means allowed I endeavoured to produce what is now called a *hard* valve. Some of the early samples were exhausted by the beautiful method invented by Sir James Dewar, depending on the absorptive power of charcoal when cooled in liquid air, for gases. In 1907 Lee de Forest, who had been following my work very closely but employing in a glass bulb a relatively low vacuum, as is shown by his reference to it in his specifications as a "gaseous medium," introduced a zigzag of wire between the filament and the anode plate, which gave the first suggestion for the control of the electron current by electrostatic action. When this suggestion was followed out by introducing into my hard rectifying valve a spiral of wire or cylinder of metal gauze, now called the *grid*, between the filament and the cylinder or plate forming the anode, we came into possession of an appliance of remarkable utility. So much has been already written and said on the subject of the thermionic valve that the elementary principles may be assumed to be well known.

When a difference of potential with the anode positive is created between the anode and the filament by a battery placed in the external circuit connecting them, a stream of electrons called the plate current flows from the filament to the plate. If we give to the grid various potentials relatively to the filament, the plate current is increased when the grid is positive and decreased when it is negative.

There are therefore three variables, viz. the plate current $i_p$, the plate voltage $v_p$, and the grid voltage $v_g$, to be considered. If we take these quantities to a certain scale to represent three rectangular co-ordinates of a point, their variation in the case of a *hard* or high-vacuum valve defines a certain surface called the *characteristic surface* of the thermionic valve (see Fig. 6). Sections of this surface give us the characteristic curves in two co-ordinates.*

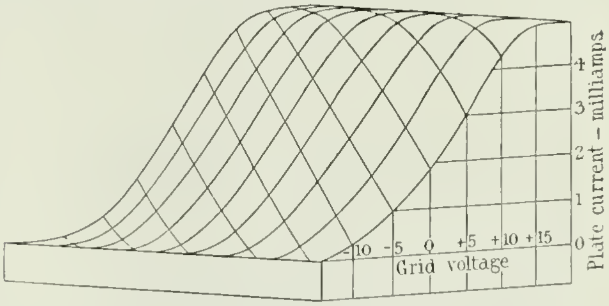


Fig. 6.—Characteristic surface of the hard thermionic R valve.

On examining the characteristic surface it is seen that there is a certain region in which it is nearly flat or plane, and hence in this district the co-ordinates fulfil the condition for the equation to a plane, viz.

$$i_p = av_g + bv_p \quad . \quad . \quad . \quad . \quad (26)$$

as first pointed out by M. Marius Latour, where $a$ and $b$ are certain parameters called the characteristic slopes.

If we take a section of the surface along any plane for which $v_p$ or the anode potential is constant, we have a curve called the grid-plate current characteristic. The central part of this curve for a hard valve is very nearly a straight line, and the top and bottom parts of the curve where the line becomes parallel to the grid voltage axis are nearly parabolas (see Fig. 7). Within the limits of variation of grid voltage for which the characteristic remains nearly a straight line any variation of this voltage results in an exactly similar mode of variation of the plate current, no matter how rapid the fluctuations of potential.

---

* See British Patent Specification No. 24850, 16th November, 1904, page 3, line 46, where occur the words: "As a very high vacuum should be obtained in the bulb and as a considerable quantity of air is occluded in the conductors, these should be heated when the bulb is being exhausted."

† See *Proceedings of the Royal Society*, 1905, vol. 74, p. 476.

* The photograph from which Fig. 6 has been prepared was taken from a characteristic surface of the hard or high-vacuum valve commonly called an R valve, so much used in wireless telephony. This surface was modelled in plaster of Paris by Messrs. W. F. Marriage and H. A. Howse from careful electrical measurements made by them in the Electrical Engineering Laboratory of University College, London.

If we create the variation of grid voltage by variation in the terminal potential difference of a suitable transformer the secondary terminals of which are connected to the grid and filament respectively, and if we connect the plate to the filament through the primary circuit of a transformer which includes also the high-voltage plate battery, then the variations of the potential difference of the secondary terminals of this last transformer will be an amplified copy of the variations of potential difference at the primary terminals of the grid transformer, provided these transformers are constructed in a suitable manner.

Owing to the complete absence of inertia and the manner in which the plate current responds instantly to changes in grid potential, the combination of suitable transformers and thermionic valve or amplifier constitutes a relay or repeater applicable to telephony, and by means of which any variation of potential at one pair of terminals is repeated and amplified at the other pair, no matter how rapid or how complicated these changes of potential may be. The construction of a thermionic repeater which will operate without distortion of speech sounds is dependent upon careful proportioning of the valve structures and the transformers and upon the limitation of the range of the grid potential to the central portion of the characteristic curve, which must be very approximately a straight line over that range. Subject to these conditions any type of good hard thermionic three-electrode valve will serve as a telephone repeater.

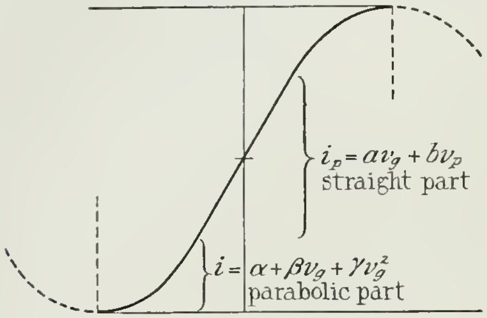


FIG. 7.—Construction giving approximately the form of the (grid voltage)-(plate current) characteristic curves for a hard thermionic valve.

The British Post Office employ a type of thermionic repeater not very different from the valve used so much in wireless reception. It comprises a drawn tungsten wire filament surrounded by a spiral wire grid, this again being embraced by a cylindrical anode. The connections from filament, grid and cylinder are brought down to a 4-pin collar fitting into a socket in such fashion that it is impossible to make wrong connections in replacing a broken valve.

The Western Electric Company of America have developed a low-temperature thermionic repeater in which the hot filament consists of a narrow strip of platinum-iridium coated with a mixture of barium oxide and strontium oxide. When the strip is heated by a current to dull red heat the oxides give off a copious evolution of electrons, as first shown by Wehnelt. The process of treating consists in mixing the carbonates of the metals with resin or paraffin and painting this mixture on the strip in several coats. After each application the temperature of the strip is raised to 1 000° F. to burn off the organic carrier. This forms a firmly adhering layer of oxide which emits electrons readily on heating to about 500° F. or 600° F. The life of the coated strip is claimed to be longer than that of the tungsten wire, which latter must be worked at a far higher temperature.

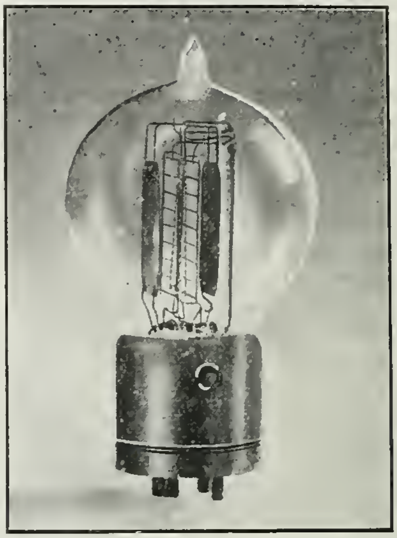


FIG. 8.—Western Electric Company's thermionic telephone repeater with oxide-coated metallic filament.

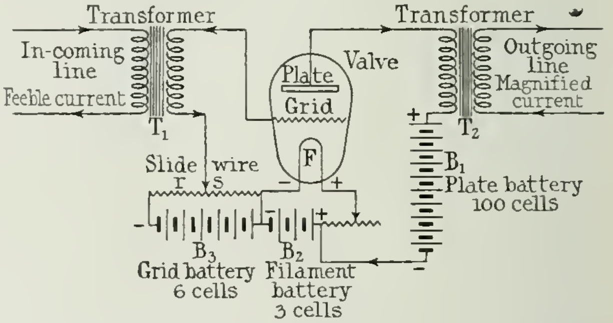


FIG. 9.—Thermionic three-electrode valve and associated input and output transformers employed as a telephone repeater.

The Western Electric Company fix this coated filament between two flat-plate anodes with very open mesh grids between (see Fig. 8). The combination of two transformers and a thermionic amplifier constitutes then a one-way telephone repeater in which the energy required for amplification of speech sound energy is drawn from the battery in the plate circuit (see Fig. 9).

If it were possible to employ independent telephone circuits for speech in each direction, and if only one repeater were necessary in the line, the above simple arrangement would meet the requirements. Telephone circuits have, however, to operate equally in both directions.

If the repeater could always be placed at the electrical centre of the line, then various modes of connection, in principle due to Edison, would enable telephone currents arriving from one direction to be re-transmitted with augmented energy to the continuation of the line.

One such mode of connection is shown in Fig. 10, taken from a paper by Sir William Noble on "The Long-Distance Telephone System of the United Kingdom."* It will be seen that the grid transformer of the repeater is connected across the line. The grid has therefore a fluctuating voltage put upon it, due to the speech currents. The plate current of the repeater passes through the primary of another induction coil and reacts on the line through a four-coil secondary circuit which comprises a pair of coils in each of the lines forming the telephone circuit. These coils are so wound that the induced electromotive forces in them drive current both forward and backward in the line circuit but do not disturb the potential difference of the points from which the grid transformer is fed, provided that the telephone circuit has an equal impedance in both directions reckoned from this feeding point.

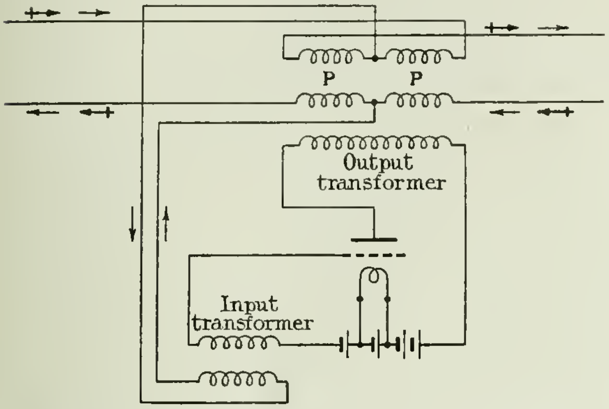


Fig. 10.—Two-way thermionic telephone repeater inserted in a telephone circuit, showing mode of connection of circuits.

The object of this connection is to prevent the plate current of the valve reacting on the grid and so causing the valve to generate oscillations which would entirely destroy its use as an amplifier. It will be seen, however, that this is only the case when the impedance of the telephone line is equal in both directions from the point of repeating.

It is seldom possible to secure this symmetry and hence in the practical arrangement the telephone line is cut at the repeater station, and each part is continued by an artificial line which exactly imitates in impedance that respective portion of the arriving or departing line. Each junction is then provided with its thermionic repeater connected as in Fig. 11, and the amplified currents from one line, say *Line East*, are transferred to the other side, say *Line West*, and vice versa. Hence we have a perfect symmetry of repeating and a circuit which can be used in either direction.

The repeater therefore produces an amplification of the telephone currents which more or less annuls the attenuation of the line.

This is called the "repeater gain" and is reckoned in miles of standard cable. Thus we may say that a certain repeater is equivalent to 15 M.S.C., which means that if inserted in a line whose equated length was 40 M.S.C. it would reduce it to the equivalent of 25 M.S.C. as far as telephonic speech is concerned.

The repeater gain in M.S.C. can be predetermined from certain other measured quantities as follows: If the characteristic curves of a thermionic valve are delineated from observations on the plate current, plate voltage and grid voltage, we can determine the valve parameters $a$ and $b$ which appear in the expression (26) for the plate current.

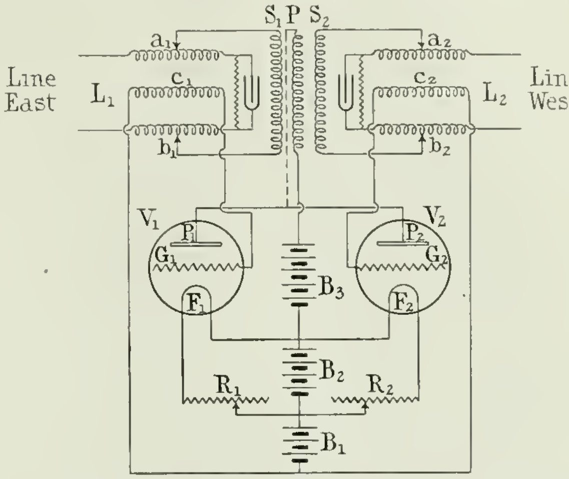


Fig. 11.—Mode of connection of two thermionic telephone repeaters in a telephone line so as to secure duplex transmission when the repeater station is not at the electrical centre of the line.

The reciprocal of the parameter $b$ is the internal resistance of the valve between filament and plate, corresponding to a certain measured plate current. The parameter $a$ is the increment of plate current with grid voltage when plate voltage is constant, and in the R valve has a value of about 1/2 000 or 1/2 500. The ratio $a/b = k$ is called the voltage amplification of the valve and is generally a number between 5 and 10. If the external plate circuit contains a coil of impedance $R$, and if $v$ is the alternating voltage applied to the grid, then it can be shown that the power imparted to the plate circuit is given by the expression

$$P = \frac{Ra^2v^2}{(1 + Rb)^2} \quad . \quad . \quad . \quad . \quad (27)$$

---

* See *Journal I.E.E.*, 1921, vol. 59, p. 389.

The above expression has a maximum value when $R = 1/b$, and under this condition $P = \frac{1}{4}bk^2v^2$.

If the grid transformer has a voltage ratio $T$ and if the line potential at the feeding point is $V$ and the line impedance $Z$, then the power $p$ given to the grid transformer is very nearly $v^2/T^2Z$.

But since the Edison circuit utilizes for forward propagation only half the power given out from the plate circuit, the magnification ($M = P/p$) for the repeater is given by the equation

$$M = \frac{bk^2T^2Z}{8} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

In the case of the standard cable the voltage attenuation per mile is $0 \cdot 1$, and hence the power attenuation for a length $l$ miles is given by the factor $\epsilon^{-0 \cdot 2l}$. Accordingly we can say that the repeater magnification $M$ is equivalent to a gain of $l$ miles of standard cable when

$$l = 5 \log_\epsilon M = 11 \cdot 5 \log_{10} M \quad . \quad . \quad (29)$$

and $M$ is given by Equation (28). The effect, then, in practice of the introduction of this type of repeater has been to enable a great reduction to be made in the weight of copper used per mile in trunk lines, because the repeater can nullify line attenuation. Thus the London to Glasgow aerial trunk telephone lines employed a double copper conductor each weighing 600 lb. per mile; in other words the whole 450-mile length involved the employment of 540 000 lb. or nearly 250 tons of copper. We may contrast with this the recently laid underground trunks from London to Manchester, 183 miles long, which were completed last year by the Post Office. This line has been equipped with repeater stations and the copper conductors weigh 40 lb. to the mile in place of the 300 lb. which would have been necessary without repeaters. This fact alone shows the enormous economy in first cost which could have been effected in the trunk-line telephone system of this country if the thermionic repeater had been in existence when they were first projected.

The completed invention of the thermionic repeater has rendered commercially possible a vast extension of telephonic range and the establishment of telephone exchanges which may extend over the area of empires or continents rather than cities or countries as suggested by our President, Mr. Gill, in his valuable Presidential Address at the beginning of this session.

## VIII. THE PROBLEM OF MULTIPLE TELEPHONY.

(15) Years ago the problem of the use of a single telegraph wire to carry simultaneously several telegraph messages was solved by the invention of duplex, quadruplex, and later on by systems of multiplex telegraphy, especially by such ingenious machine telegraphs as those of Baudot and Murray. The analogous advances in telephony have been slower in arriving, but the magic thermionic valve has given us not only the solution of the telephone repeater problem but also the valuable carrier-wave multiple telephony. The adoption of phantom working was one of the first steps in effecting an economy of conductors.* When we have a pair of mutually non-inductive double-wire circuits, whether twisted aerial or quad cable, we have a pair of circuits, called the side or physical circuits, through which two independent telephone conversations can be conducted. But we can employ also one pair taken together as the lead and the other pair taken together as the return of a third or phantom circuit. In some cases we can use all four wires as a lead and an earth return to make a fourth circuit.

Not only can we load with Pupin coils the two side circuits, but extremely ingenious modes of coil winding with four wires have been devised which enable us to load the phantom circuit independently of the two side circuits. Phantom-circuit working and loading is now very extensively carried out in the telephone circuits of the United Kingdom and in the United States.

A further mode of effecting economy in conductors is the utilization of existing telegraph wire circuits for simultaneous telephony.

It would occupy too much space to describe in barest outline a fraction of the work done in this department since the method first introduced in 1882 by F. Van Rysselberghe gave an impetus to further invention, which was continued by Mr. C. L. Langdon-Davies in his ingenious Phonopore and finally reached a stage represented by the Fullerphone of Major Fuller.* The most recent practice in this development, particularly the use of circuits called *composited* circuits, was described in a paper last year by Mr. J. G. Hill entitled "Phantom Telephone Circuits and Combined Telegraph and Telephone Circuits Worked at Audio Frequencies." † Hence it will not be necessary to make further reference to this part of the subject.

(16) On the other hand new and important methods of multiple telephonic working have been lately introduced in the form called "carrier-wave" telephony, which depend on the use and properties of the thermionic valve. A few explanations of this method may therefore be of interest. It will be necessary to assume that the methods of connection and the process by which the three-electrode valve is used to produce high-frequency oscillations are familiar. Also a knowledge of the broad general principles of apparatus used for radio-telephony must be taken for granted. In radio-telephony we set up high-frequency oscillations in an aerial wave by means of a valve generator, and we control the amplitude of these oscillations by appliances which include a speaking microphone so that the amplitude of the high-frequency oscillations is varied in accordance with the wave-form of the speech sounds. We therefore produce two simultaneous sets of electric vibrations, one a high-frequency sine-form oscillation, and superimposed on this a low- or audio-frequency speech current (see Fig. 12). These complex aerial currents radiate electromagnetic waves of an identical character. At the receiving end the waves are absorbed by the receiving aerial and rectified by the receiving valve and then passed through a receiving telephone which reproduces the speech sounds made to the transmitter microphone.

---

* The earliest patent application in Great Britain for that mode of connection called phantom working was made by Mr. F. Jacob in British Patent Specification No. 231, of 1882.

* See *Journal I.E.E.*, 1919, Supplement to vol. 57, p. 20.

† See *Journal I.E.E.*, 1922, vol. 60, p. 675.

In the above-described arrangement the high-frequency electric waves are used to carry to a distance variations of their own amplitude and are therefore called *carrier* waves.

If we imagine the sending and receiving aerials to be connected by a wire, these waves would not be able to disperse in all directions but would be guided along the wire. The arrangement is then called guided-wave or carrier-wave telephony, as contrasted with radio-telephony.

In the above very rough description of the process we have not sufficiently indicated the manner in which the voice currents are superimposed on the carrier currents at the sending end, or disentangled from them at the receiving end. It is necessary then to explain a little more in detail the properties of the thermionic valve which enable it to be used as a *modulator* and *demodulator* in carrier-wave telephony.

The general form of the plate current-grid voltage characteristic curve of the three-electrode valve has already been described. It consists of a nearly straight middle part and two curved extreme portions which are nearly semi-parabolas in shape.

No simple algebraic expression can be given as the equation to the whole curve, but as long as we limit our attention to the lower parabolic part we can nearly express the plate current $i$ in terms of the grid voltage $v$ by an equation of the form

$$i = a + bv + cv^2 \quad . \quad . \quad . \quad . \quad (30)$$

where $a$, $b$ and $c$ are certain constants. As already stated, we utilize the straight-line part of the characteristic curve in amplifying, repeating or generating oscillations by the valve. We have now to explain the manner in which we use the curved extremities in modulating and demodulating electric oscillations. Suppose we give to the grid of a valve a sufficient negative potential to bring the operating point down on the lower curved part of the characteristic curve, and then superimpose upon that steady voltage a small high-frequency alternating voltage. It is easy to see that the result will be to produce ripples on the plate current or to create a plate current which has a steady part and a superimposed alternating part, and is slightly distorted as compared with the alternating grid voltage (see Figs. 13 and 14).

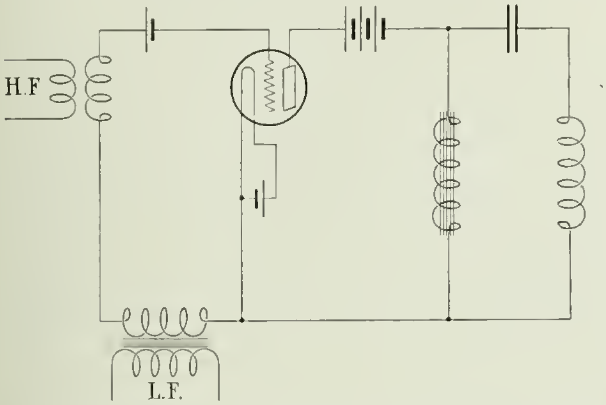


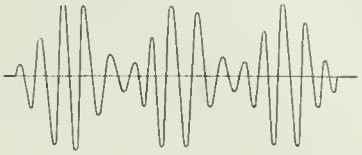
FIG. 12.—Diagram showing the mode of superimposing low frequency (L.F.) and high frequency (H.F.) voltage variations on the grid of a thermionic valve.

If we apply, in series with the high-frequency voltage, a low-frequency voltage to the grid so that the resultant grid potential is represented by

$$v = E_1 \sin pt + E_2 \sin qt \quad . \quad . \quad . \quad (31)$$

where $p/2\pi$ is the high frequency and $q/2\pi$ the low frequency, then by substitution in Equation (30), neglecting the constant term, we have for the resulting plate current the expression:—

$$i = bE_1 \sin pt + bE_2 \sin qt + cE_1^2 \sin^2 pt + cE_2^2 \sin^2 qt + 2cE_1E_2 \sin pt \sin qt \quad . \quad (32)$$



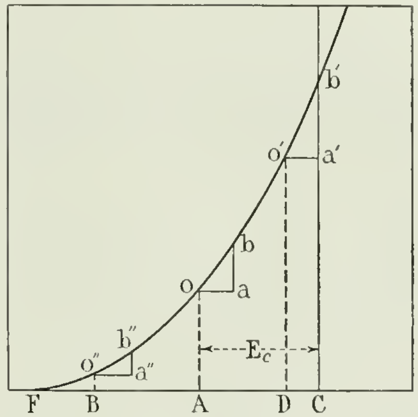


FIG. 13.—Diagram showing the manner in which small equal increments of grid voltage represented by Oa, O′a′, O″a″, applied at various points in the curved part of the characteristic curve of a thermionic valve produce different increments of plate current represented by ab, a′b′, a″b″, and so modulate the anode current.

But $\sin pt \sin qt = \frac{1}{2}\cos(p-q)t - \frac{1}{2}\cos(p+q)t$ and $\sin^2 pt = \frac{1}{2} - \frac{1}{2}\cos 2pt$. Hence it is seen that in the resulting complex plate current there are oscillations of six different frequencies, viz. $2p$, $p$, $p-q$, $p+q$, $q$ and $2q$, each divided by $2\pi$.

The plate-current wave-form is then not a copy of the grid potential wave-form when we are operating on the curved parts of the characteristic curve, as it is when we employ the straight central part, but the plate current has a different wave-form from that of the grid potential and is said to be *modulated*. A valve so used for this purpose is called a modulating valve. Suppose then that the high-frequency current of frequency $p/2\pi$ lies near or above the limits of audition, say 10 000 or so. This frequency is called a *carrier frequency* and currents of that order of frequency are called carrier currents.

Let the low-frequency current of frequency $q/2n$ lie within the voice frequency range, say 200 to 2 000 p.p.s. Let us suppose that $p/2\pi = 10\,000$ and $q/2\pi = 1\,000$. Then in the modulated current there will be components of frequencies 11 000, 10 000, 9 000 and 1 000.

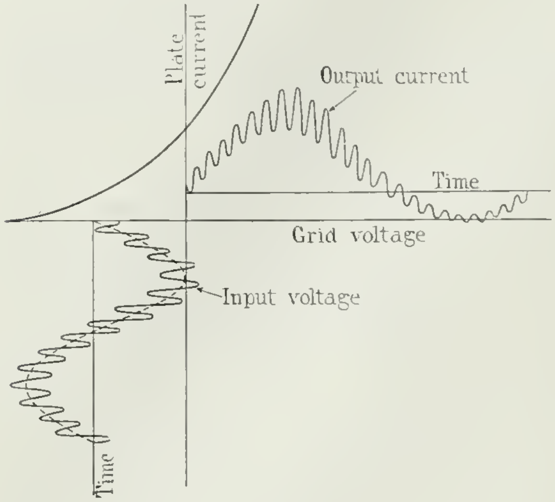


Fig. 14.—Diagram showing the mode of variation of the plate current of a three-electrode thermionic valve when simultaneous variations of low and high frequency potential are imposed on the grid at the lower part of the characteristic curve.

It is possible to sift out currents of certain ranges of frequency by means of devices called *electric filters*, which are short, artificial lines built up of inductance coils and condensers arranged in certain ways. Thus if the inductances are placed in series and the condensers in shunt (see Fig. 15) we have a filter called a *low-pass filter* because it permits low-frequency currents to be transmitted through it, but very rapidly attenuates currents of high frequency.

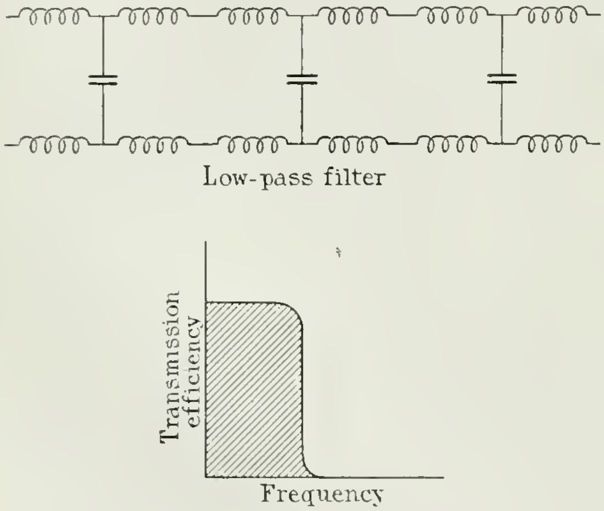


Fig. 15.—Diagram of a low-pass filter circuit.

If we arrange the condensers in series and inductances in shunt (see Fig. 16) we construct a *high-pass filter*, so called because it blocks out low-frequency currents below a certain frequency.

Again, by arranging certain inductance-capacity shunts as in Fig. 17 we construct a filter called a *band filter*, so called because it has the property of allowing currents the frequency of which falls within a certain band or limits to pass, but rapidly attenuates those of higher and lower frequency.

It has been primarily due to the invention and study of these filters, especially by G. A. Campbell and others, that carrier-wave telephony has been rendered possible.

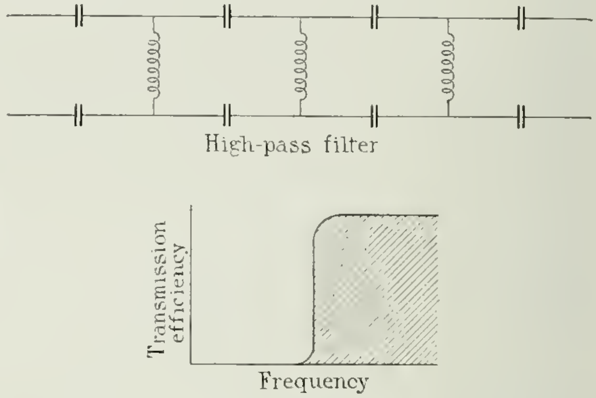


Fig. 16.—Diagram of a high-pass filter circuit.

Returning then to our modulating valve let us suppose that the low-frequency applied grid voltage has not a pure sine-curve form but is complex and therefore resolvable into components of different frequencies as in speech waves, lying between the limits of 200 and 2 000 or thereabouts. It is clear, then, that the $q$ in our above formula is to be taken as representing a whole range or band of frequencies forming a sort of electrical spectrum, and the same applies to the $p + q$ and $p - q$ frequencies in the above formula. It is possible to arrange a band filter which when interposed in the circuit of the plate current of the modulating valve will block out all frequencies except those of $p/2\pi$ and $(p + q)/2\pi$, viz.

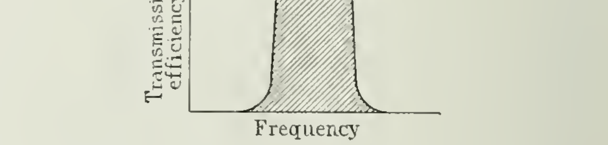


Fig. 17.—Diagram of a band-pass filter circuit.

those of the pure carrier current, and are of the bands due to the addition of the range of voice frequencies to the carrier frequency. In the instance given above this would mean that the filter transmits frequencies of the band from 12 000 to 10 200 and also 10 000 for the carrier current. Currents of these frequencies can then be transmitted along an ordinary telephone line without interfering with the propagation of the ordinary telephone currents of voice frequency. Let us consider in the next place the result of allowing the group of high-frequency currents, or rather electromotive forces created by them by means of a suitable transformer, to act on the grid of a thermionic valve at the receiving station, called a demodulating valve. We have seen that when frequencies $p/2\pi$ and $q/2\pi$ act on the grid at a point on the lower part of the characteristic curve, we have produced a plate current involving 4 different frequencies, viz. $p/2\pi$, $(p+q)/2\pi$, $(p-q)/2\pi$ and $q/2\pi$. Hence it is clear that if voltages involving frequencies $p/2\pi$ and $(p+q)/2\pi$ act as a grid, the resulting plate current will contain frequencies $p/2\pi$, $(2p+q)/2\pi$, $(p+q)/2\pi$ and $q/2\pi$; all but the last are relatively high-frequency currents and can be filtered off from the band of voice currents of frequency $q/2\pi$.

These last can then be rectified and allowed to act on a telephone receiver and thus re-create the speech sounds made to the transmitter coupled to the grid of the modulating valve at the sending end. Hence the broad principles of multiple carrier-wave telephony can be outlined as follows :—

At one end of an existing long-distance telephone line used in the ordinary way for telephonic speech we can attach a certain number of modulating valves with their plate circuits coupled to the line through appropriate transformers and filters. We can then generate by means of a number of oscillating valves high-frequency carrier currents of certain different frequency and apply electromotive forces due to these in series with the electromotive forces of low or speech frequency produced by ordinary carbon microphone transmitters, so as to give to the grids of the several modulating valves carrier-frequency plus voice-frequency voltages (see Figs. 12 and 14). These carrier frequencies $p/2\pi$ must be so selected that the respective bands of modulated frequencies represented by $(p+q)/2\pi$ (where $q/2\pi$ is the range of voice frequency) do not overlap. We then transmit all these currents along the telephone line and at the receiving end separate out the several groups of oscillations by suitable band filters and apply the electromotive forces created by suitable transformers to the grids of demodulating values. In the plate circuits of these last valves we have coupled ordinary telephone receivers which are acted upon by the voice currents disentangled by these demodulating valves from their respective carrier currents (see Fig. 18).

Each telephone receiver then repeats the speech sounds made to the corresponding microphone transmitter at the sending end.

In this manner we can make a single telephone line convey simultaneously a number of telephonic conversations through the agency of a number of superimposed separate carrier currents, the frequencies of which are far enough apart to prevent the corresponding bands of modulated currents from overlapping as regards frequency.

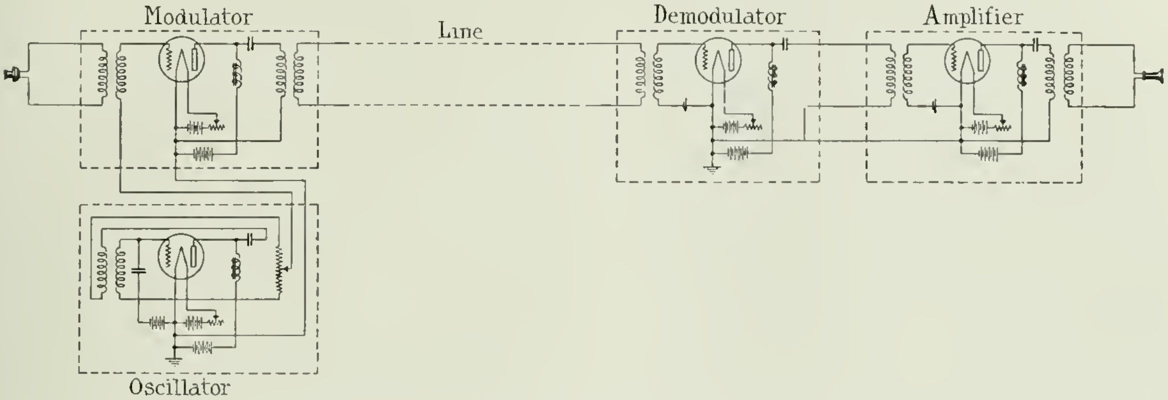


Fig. 18.—Diagrammatic scheme of circuits (omitting all filters) to illustrate the general principle of carrier-wave multiple telephony (Colpitts and Blackwell).

In securing, however, good results as to speech clearness in this carrier-wave telephony certain precautions are necessary, which perhaps may best be stated in the words of Messrs. E. H. Colpitts and O. B. Blackwell in their paper on " Carrier Current Telephony and Telegraphy," read at the Midwinter Convention of the American Institute of Electrical Engineers, February, 1921. They say : " It is necessary to consider the interactions between the frequency components of the side band itself, for if in the case of telephony the voice wave includes components of more than one frequency, each will be represented by a corresponding component in the side band. The interaction of two of these component frequencies simultaneously present in the side band give rise to a component in the output circuit of the demodulator, the frequency of which is the difference between those of the corresponding two components in the original voice wave. Such currents will have a serious effect on the quality of the reproduced speech if their amplitude is comparable with that of the reproduced voice currents. The amplitude of this distorting component is proportional to the product of the amplitudes of the two side-band components, whereas the amplitude of each of the two components of the desired voice current is proportional to the product of the amplitudes of its corresponding side-band component and that of the carrier. The reproduced voice current can be made large compared with the distorting current only by ensuring that the carrier current is large compared with every component of the side band. As the result of this it follows that in order to secure a good quality of speech it is necessary that the greater part of the energy applied to the demodulator consist of unmodulated carrier frequency."

It is clear therefore that to obtain good carrier-wave telephony we have to send along the line a relatively large amount of electric current in the form of unmodulated carrier current. This has led to a curious improvement which is called the suppressed carrier-wave system, in which the required surplus of unmodulated carrier current required to prevent speech distortion is not sent along the line, but supplied from a local source at the receiving end. This necessitates, however, special arrangements to secure that the added carrier current at the receiving end shall have exactly the same frequency as that supplied to the modulating valve at the sending end. The reduction of the carrier current has two advantages besides that of employing smaller line currents. It has been pointed out that the amplitude of the speech currents in the demodulator output circuit is proportional to the product of the amplitudes of the carrier current and that of the corresponding side-band component. Any changes in the leakance of the line by affecting the attenuation of the carrier current affects the loudness of the reproduced speech. This cannot occur when the greater part of the high-frequency carrier current is supplied at the receiving end. Again, interactions between the carrier current and any other stray currents due to cross-talk or want of perfect balance in the circuits are less prominent in the suppressed carrier-wave system. The carrier-wave system can be applied also in the transmission of telegraphic signals on Morse code, as well as to telephony. In the case of telegraphy it is not necessary to transmit such wide side-bands, or bands the frequency of which range over the same extent as are required for telephony. The result is that a much larger number of independent side-bands can be accommodated on one line without mutual interference, and therefore a larger number of simultaneous telegraph messages can be transmitted than is possible with multiple telephony.

To-day one telephone wire between New York and Chicago carries at the same time with complete privacy five independent telephone conversations, and also certain sections of the line carry 40 different telegraph messages each way. In this manner a single line does duty for 85 communications at once, if necessary. Having regard to the fact that in long-distance working the capital outlay on the line and therefore the corresponding annual charges for interest and depreciation are the heaviest items, it will be seen that this carrier-wave telephony and telegraphy is of immense importance.

(17) Some special difficulties in connection with the propagation and amplification of these high-frequency currents may be mentioned very briefly.

The propagation of high-frequency currents along telephone aerial lines or through cables follows the same general principles as in the case of low- or audio-frequency currents. The inductance and capacity of the lines have much the same values for high as for low frequency. The resistance taken into account must, however, always be the high-frequency resistance as determined by the frequency. It is well known that the leakance of an aerial line is very much greater for high than for low frequency; at 25 kilocycles it may even be 200 times as great, even in quite dry weather. This appears to be connected with the well-ascertained fact that the conductance of dielectrics increases rapidly with the frequency in many cases.*

Hence we find that the attenuation of a line increases very rapidly with the frequency. For reasons which it is hardly necessary to state in detail, lines which are coil-loaded on the Pupin system are not suited for carrier-wave telephony, owing to the reflection losses which take place at the points where the loading coils are inserted. There is not such difficulty with uniformly loaded cables. Through the uniformly loaded submarine cables laid between Key West in Florida and Havana in Cuba the already mentioned carrier-wave telephony and telegraphy are quite successfully conducted in both directions. In the case of uniformly loaded submarine telephone cables it is an advantage to keep the carrier frequency as low as possible because the attenuation rapidly increases with frequency and it is, of course, impossible to insert repeaters in the run of a submarine cable. In the case of land lines and at the ends of submarine cables the attenuation can be neutralized by the introduction of thermionic repeaters. There are some peculiarities in connection with amplification in lines conveying multiple carrier telephonic currents, which may be mentioned. It would, of course, be possible to separate out the various bands of frequencies belonging to different channels of telephonic speech, at any locality by suitable band filters and then amplify each by a separate thermionic repeater and return the amplified currents to the common line. But it is not necessary thus to separate them out. We can amplify the whole complex group by one or more thermionic repeaters in parallel. There is, however, in the case of carrier-wave telephony, a liability for the repeater to act as a modulator if we extend the grid potential variations beyond narrow limits. To nullify this action the repeaters are worked in pairs. The incoming currents act so that the grid of one valve is increased in potential at the instant when that of the other is lowered by an equal amount. The output currents then co-operate together through the transformer and their combined energy is conveyed to the line. On the other hand, any currents which have their origin in the valves owing to modulation are in opposition as regards phase and cut each other out.

---

* See J. A. Fleming and G. B. Dyke: "On the Power Factor and Conductivity of Dielectrics," *Journal I.E.E.*, 1912, vol. 49, p. 323.

It should be mentioned that a two-way repeater plant suitable for use with carrier-wave telephony has been developed, and also that the arrangements for full duplex in the case of carrier-wave telegraphy have also been worked out by the American Telephone and Telegraph Company in conjunction with the Western Electric Company of America.

It may perhaps be added that carrier-wave telephony and telegraphy in the present state of the art find their commercial justification only in application to relatively long and therefore expensive lines.

## IX. The Problems of Commercial Telephony.

(18) The great advances in the development of commercial telephony centre round three remarkable groups of inventions connected with the working out of the telephone exchange system. These are (i) the Common-Battery System, (ii) the Multiple Switchboard and (iii) the Automatic Telephone Exchange. The use of the telephone would probably have been comparatively limited if it had not been for the conception of a telephone exchange for mutual conversation. This may be said to have originated with Bell almost immediately after he and others had given us the means of talking along a wire. It was the success which attended even the first crude attempts to establish an exchange system which created the necessity for grappling seriously with the unsolved problems in connection with it. To deal even in barest outline with the manner in which the problems of exchange telephony have been approached and fairly well solved would require not merely a fragment of a lecture, but a long course of lectures. Moreover, the literature of the subject is extremely extensive. The masterly treatise of our member, Mr. J. E. Kingsbury, on "The Telephone and Telephone Exchanges" (Longmans, Green & Co.), covers the broad general history and special treatises, and papers without number supply abundant technical details. Hence I shall not attempt to repeat that which has already been so well said.

The development of the automatic exchange is a story of fascinating interest. It presents us with a galaxy of inventions of astounding ingenuity, the result of which has been to give us a mechanical appliance which is almost a living organism in its capabilities and adaptability to the requirements of human intercourse.

## X. Some Problems of Radio-telephony.

(19) The very remarkable progress in radio-telephony during and since the European war has been chiefly due to the wonderful intrinsic powers of the three-electrode thermionic valve, which have been brought to light by the researches and inventions of numerous investigators of the highest ability.

An achievement which a few years ago was the occasional and imperfectly performed feat of experts has now become a popular pastime, with apparatus for it sold in countless shops.

Still there are many problems connected with radio-telegraphy as yet imperfectly solved, although astonishing progress has been made in some respects in the last few years.

Limiting our consideration solely to the subject of speech transmission by radio we find that in the transmitting part of the appliance as generator of the carrier electromagnetic waves required, the thermionic valve has displaced all other rivals such as the arc and high-frequency spark. It is questionable whether high-frequency alternators or Poulsen arcs will survive in competition with the valve. As long as we are concerned only with small-power radiation the glass-bulb high-vacuum three-electrode valve provides a very convenient generating appliance. Assuming that it is not too badly treated during the progress of manufacture by the electron bombardment of the metallic parts and consequent wear of the filament, it has a fairly satisfactory life.

Even up to a power of 5 kW the glass-bulb valve is still a very practical appliance, although silica bulbs have been used for somewhat larger powers. Methods of using a large number of valves of, say, 5 kW capacity in parallel have been perfected, as in the large valve panel at Marconi's Wireless Station, Carnarvon, where 60 or more valves of the above size are employed in parallel. For larger powers and in prolonged use the heating of the anodes sometimes gives trouble.

An advance which has been made during the past year is therefore the discovery of a method of constructing high-power valves with bulbs partly of metal and partly of glass. The metal part also forms the anode and can be kept cold by water circulation or air cooling. This new type of valve was rendered possible by the discovery of a method of sealing together a glass and a copper-plated nickel tube. Hitherto it has been necessary to convey the currents into and out of the glass bulb by platinum wires sealed through lead glass. The present high price of platinum (about £23 per ounce) prohibits any extensive use of this metal.

Some years ago Mr. W. G. Housekeeper, of the Bell Research Laboratory of the Western Electric Company, U.S.A., endeavoured to cheapen the production of telephone switchboard incandescent lamps by the use of copper instead of platinum for leading-in wires. Copper is possessed of one of the qualities necessary for an air-tight seal through glass, viz. that it is "wetted" by molten glass and adheres to it. Copper and glass have, however, quite different coefficients of expansion. It has been found that a thin nickel copper-plated tube provided with a knife-edge end can be sealed air-tight to a glass tube and the joint will not crack on cooling or on re-heating. Hence the construction of a metal-glass bulb thermionic valve for large power can be carried out as follows:—

A copper tube 3 or 4 inches or more in diameter closed at one end has a copper-plated nickel ring welded to one end which has a sharp bevel at the free edge. This can be sealed on to a glass tube. The copper tube is provided with a jacket and can be water-cooled.

The glass portion has a re-entrant end through which copper leads are sealed to convey the filament heating current and also the connection to the grid, provided it is a three-electrode valve. It will be remembered that our President, Mr. F. Gill, exhibited some months ago to the Institution some 10-kW three-electrode valves of this type made by the Western Electric Company. The filaments of these valves are stout tungsten wires, and take 24·5 amperes at 32 volts to bring them to bright incandescence. The normal plate voltage is 10 000 volts supplied from a d.c. dynamo or by rectified low-frequency alternating voltage. The power intake of the tube, including filament-heating, is 15 kW and the efficiency 75 per cent. The General Electric Company of America have also been working along the same lines in the development of high-power valves. They have produced a 20 kW valve, comprising a copper anode tube which forms part of the bulb and is about 1·9 inches in diameter and 8 inches long. This is sealed to a glass tube 2·75 inches in diameter at the widest part.

The filament of this valve is a stout tungsten wire 1/25 inch in diameter and is heated by a current of 50 amperes supplied at 20 volts. The plate voltage is 15 000 volts and the overall efficiency of the valve as a generator is about 70 per cent.

A 100 kW valve of the same type is being developed by the same corporation. I have seen some similar valves of 150 kW power made by a firm in Holland. An additional advance which may have important consequences in connection with high-power generating valves consists in abolishing the grid and returning to the simple two-electrode or Fleming valve as an oscillation generator on the following principles. If a straight rod, say of tungsten, is made incandescent in a high vacuum, it emits, as we know, electrons normal to its surface. If the filament is surrounded by a cylindrical anode kept at a high positive potential, these electrons move radially towards the anode, creating a thermionic current. The filament-heating current, however, produces a circular embracing magnetic field and the moving electrons are therefore acted upon by a force tending to make them move across these lines of force in a direction parallel to the filament, or even bring them back towards it.

If, then, the filament is heated by a high-frequency alternating current the temperature and therefore electronic emission keeps nearly constant, but during the instants of maximum filament current there will be a force reducing the thermionic current, which last, however, will rise to its full strength during the instants when the filament-heating current is zero.

Accordingly, if the straight filament of a two-electrode valve with cylindrical anode is heated by a strong high-frequency alternating current, say of 20 000 p.p.s., and if a high positive voltage is put upon the anode, the thermionic current in an external circuit connecting the anode and the filament will have pulsations in it having a frequency twice that of the filament-heating current. These pulsations may, by a proper transformer in the external anode circuit, be converted into high-frequency alternating current.

The valve so used becomes a sort of alternating-current transformer or converter of part of the energy of a direct high-voltage current into high-frequency alternating current. In place of the electrostatic control of the thermionic current by the grid potential we have magnetic control by means of the field, due to the filament-heating current.

In the author's fundamental patent for the thermionic valve in 1904 it was pointed out that if the filament were heated by a high-frequency alternating current, the thermionic current in an external circuit connecting the anode and filament was a direct current, but it appears to have been first suggested by Dr. A. W. Hull that the field of the filament currents, if alternating, would produce pulsations in the thermionic current as above described. On these lines the General Electric Company of America are said to be developing a 1 000 kW metal-bulb thermionic generator in which the external water-cooled anode which forms part of the bulb is 30 inches long and 1·75 inches in diameter. In the axis of this anode cylinder is a tungsten rod 0·4 inch in diameter which acts as filament and is made incandescent by an alternating current of 1 800 amperes at a frequency of 10 000 p.p.s., the filament taking 20 kW. The anode d.c. voltage is 20 000 volts and the valve will supply 1 000 kW with an efficiency of 70 per cent.

Since the frequency of the generated current is twice that of the filament-heating current, it may be possible, by a series of such valves starting with a low-frequency filament-heating current for the first valve, to build up a high-frequency high-voltage current using the thermionic current of one valve to heat the filament of the next, and so on.

No great difficulty seems to have been found in making and keeping a high vacuum in these metal-bulb valves. Quite small generating valves are now being made in which part of the bulb is an air-cooled metal cylinder which forms the anode or plate, and the remainder of the bulb is of glass. The anode can be kept cool by keeping the metal part in water.

Hence the valves can be run for long periods of time at a thermionic current density on the anode which would destroy in a short time the internal anode of a glass-bulb valve. Time alone will show how these metal-bulb valves compare in life and efficiency with the glass- or silica-bulb valves. It cannot be said, however, that at the present time there is a field of operation for such large sizes in single valves.

The utility of long-distance wireless telephony is to a considerable extent frustrated by the great difference between the day and night transmission range, and especially by the as yet unconquered problem of atmospheric disturbances. So far, most of the remedies or schemes for the elimination of these disturbances have in actual practice been found to fall very far short of the claims made for them by their inventors. The chief unsolved problem in long-distance radio working is this annulment of strays. Much which may in time lead to further inventions for their conquest is being done towards a clear comprehension of the origin and source of these disturbances.

(20) Another radio problem which awaits full solution is the manner in which the electromagnetic waves sent from broadcasting stations are, so to speak, lifted over certain districts so that the speech and music are in certain cases better heard at remote than at nearer distances. It has been stated that the London radio broadcast is heard better in Scotland than in Yorkshire, and that that from Manchester is better heard at Southampton and Portsmouth than in London. Furthermore, there are "blind spots" in certain areas where the radio speech or signals are very badly heard or not heard at all, even when well within normal range of the transmitting station. Moreover, it is well known that there is a phenomenon called "fading" in which the sounds or signals carried by certain wave-lengths, especially over long distances, fade away and then reappear and fluctuate in strength in an exasperating manner. These abnormalities are probably capable of explanation by reflection from higher ionized levels of the earth's atmosphere, by absorption of wave energy by ionized masses of atmospheric gases, or by absorption in passing over certain kinds of terrestrial surface. There are very similar phenomena in the case of sound waves in air. Loud sounds are sometimes heard at great distances from the source better than at places nearer to it. This is explained as being due to the action of winds or air currents which advance and then ultimately retard the progress of the upper part of the air-wave front which causes the wave direction to be directed first upwards and then brought down again so that the sound wave, so to speak, plays "leap-frog" over certain districts.

In the case of electric waves, especially of the somewhat short wave-length used in broadcasting, the wave might be deflected upwards by reflection from certain inclined ground surfaces or by retardation of the part of the wave-front due to an increase of the dielectric constant of the air by water vapour, and then brought down again by reflection from the under surface of masses of ionized air in the upper atmosphere and so convey more energy to a distant receiving station than to a nearer one. The "blind spots" may perhaps be due to interference between waves which have reached that spot by two independent paths of different length. In these and innumerable other unsolved problems of radio-telephony very valuable contributions could be made towards their solution by the combined action of the very numerous amateurs who now possess radio-telephonic receiving apparatus.

In all large towns there are now radio societies and wireless clubs the offspring of the parent Institution, The Radio Society of Great Britain.

If programmes could be drawn up and certain standard apparatus used and methods of recording results unified, extremely useful information, which would greatly aid in arriving at explanations of some of the above-mentioned effects, could be obtained in time as to atmospheric disturbances and audibility of given broadcast in various districts, by observations made by amateur listeners-in.

Many of the most interesting problems as yet unsolved in radio-telephony can only be attacked by team work and will not yield to isolated efforts. The various problems connected with commercial radio-telephony have been mentioned and briefly discussed quite lately in a report made by a Sub-Committee on Radio-telephony to the Radio Research Board of the Department of Scientific and Industrial Research. They have considered the matter from the point of view of: (1) Long-distance working, viz. 3 000 miles or so; (2) medium distances, over 1 000 miles or so; and (3) short distances, of over 100–200 miles or so.

They point out that the very long wave-lengths most suitable for long-distance radio-telegraphy, viz. 10 000 to 25 000 metres, are unsuitable for radio-telephony, and that the power required for given long-distance radio-telephony would be from 3 to 20 times that required for similar radio-telegraphy over the same range. Also, of course, the absence of privacy and the atmospheric interferences are drawbacks as yet not overcome. We are probably, therefore, not yet within reach of means by which world-wide broadcasting is practicable, although many feats of long-distance radio-telephony have been carried out where cost and secrecy were of no account. The same criticisms apply, but perhaps not so strongly, to the medium-distance working of 1 000 miles or so.

On the other hand, for short distances radio-telephony finds a distinct field of usefulness, apart altogether from the broadcasting which may be regarded chiefly as a new form of popular entertainment. The employment of short waves 10 to 15 metres in length in conjunction with parallel-wire parabolic reflecting mirrors, as described by Mr. C. S. Franklin in a paper * to this Institution a year ago, has made a distinct advance towards privacy of communication.

With this short-wave apparatus atmospheric disturbances are much less easily picked up at the receiving stations, and listening-in by outsiders is rendered more difficult by reason of the special receiving arrangements required.

On the other hand, for short or moderate ranges radio-telephony enables us now to bridge over gaps in wire telephonic systems and to cross sea channels by means which are often less costly than the laying of submarine telephone cable might be.

The thermionic repeater and amplifier enables us to relay from wire to wireless and vice versa, and thus automatically to interconnect two exchange systems or from an exchange system to an aeroplane or airship.

In the interconnection of exchanges the two-way transmission is best achieved by the use of carrier waves of slightly different frequencies. This method can be illustrated by the recent interconnection by the American Telephone and Telegraph Company of the mainland telephone exchange system on the west coast of the United States embracing Los Angeles in California, and the exchange system of Avalon, a town in Santa Catalina Island, 30 miles off the mainland in the Pacific Ocean.

The mainland exchange system operates a radio

---

* *Journal I.E.E.*, 1922, vol. 60, p. 930; also the *Wireless World and Radio Review*, 1922, vol. 10, p. 219.

transmission to Santa Catalina with a carrier wave 470 m in length, and Avalon speaks back to the mainland with a carrier wave of 400 m.

The telephonic currents arriving from the exchange system are amplified by a valve repeater, and after passing through a low-pass filter are employed to modulate the radiated carrier waves sent out by a valve transmitter.

In reception the arriving waves are caught on a frame aerial so set as not to be influenced by the sending aerial on the same side ; and then after amplification by a valve repeater, and filtration, pass back through a hybrid coil or Edison circuit into the exchange circuits.

The difficulties of simultaneous reception and transmission or " cutting in " are for practical purposes overcome by the use of this two-wave system, and by the frame and open-wire aerials separated by a little distance. Limitations of time and space, however, prevent further reference to the details.

## XI. CONCLUSION.

(21) A brief reference may be made in conclusion to the position of research on telephonic problems in Great Britain.

The great technical corporations in the United States, such as the American Telephone and Telegraph Company, the Western Electric Company and the General Electric Company maintain research staffs and laboratories for this purpose with equipments which, as far as I know, have few equivalents in this country. They retain the services of scientific investigators of the highest ability who direct their attention not exclusively to problems of immediate commercial advantage but look far ahead into the possible requirements of the future. The only research establishments we in Great Britain possess which are on a par with those of America are the new and finely equipped laboratories of the General Electric Company at North Wembley, the National Physical Laboratory at Teddington, and, on a smaller scale, the British Post Office Research Laboratory at Dollis Hill. There is, however, in Great Britain too much tendency to demand an immediate commercial return or at any rate a very close connection between the character of the research work done and its industrial applications, and also to consider that it can be fostered by small-scale expenditure on scholarships or committees, or usefully conducted by men of mediocre power. The first essential is to find the men with great initiative and original power and then to place at their disposal adequate resources for research.

It is a lamentable thing, for example, that low-temperature research, of which the foundations were laid at the Royal Institution of Great Britain 20 or 30 years ago (when the late Sir James Dewar first liquefied oxygen, air and hydrogen in bulk in open vacuum vessels), practically ceased after the war for want of financial support ; whereas it is still active in other countries such as Canada and Holland. Telegraphy and telephony being under Government control in this country there is less inducement for private investigators of high ability to make it the subject of their labours. There is not, as far as I am aware, a single University in this country which possesses in its electrical engineering departments the necessary equipment for conducting advanced experimental investigations in telephony and telegraphy.

Nevertheless, research in this subject is a matter of national importance, especially to Great Britain with an Empire scattered over many seas.

We have never been deficient in the possession of men of the highest scientific originality in this country, but the pioneer work of such great investigators as D. E. Hughes, Oliver Heaviside, the late Lord Rayleigh and even that of Lord Kelvin himself was not at the time of its performance estimated at its true value or followed up with sufficient resources in the field of large-scale experiment, with the result that much of its practical outcome has reached us from other countries than our own. The unsolved problems in telephony are still many and of absorbing interest, and it is desirable that the attack on them should be from many sides, and not limited to the personnel of Government Laboratories or to the official initiative of small Government Committees, but that facilities should exist for bringing to bear upon them the highest theoretical knowledge and most copious experimental skill wherever found. These two rarely united kinds of ability were combined together in a surpassing degree in Lord Kelvin, and we cannot afford to allow the country which gave birth to him to fall behind in the effort to advance our knowledge of electric and magnetic phenomena, especially in relation to the arts of telephony and telegraphy, which have become of such supreme importance in relation to the intercourse of all mankind.

## APPENDIX I.

In the case of wave motion through a medium, each specific quantity which defines the state of the medium at any point in space and at any time must satisfy a certain differential equation called the wave equation. This equation is the mathematical expression for the fact that the quantity under consideration is periodic both in space and with time and is therefore propagated as a wave.

The wave equation is :—

$$\frac{d^2\phi}{dt^2} = c^2\left(\frac{d^2\phi}{dx^2} + \frac{d^2\phi}{dy^2} + \frac{d^2\phi}{dz^2}\right) \quad . \quad . \quad . \quad \text{(i)}$$

where $x$, $y$ and $z$ are the co-ordinates of a point at which the variable state $\phi$ exists at a time $t$, and $c$ is the velocity of propagation.

In the case of wave propagation from a centre uniformly in all directions, if we take the centre as origin and $r$ as the radial distance of any point the co-ordinates of which are $x$, $y$ and $z$, then :—

$$r^2 = x^2 + y^2 + z^2$$

and

$$rdr = xdr + ydy + zdz \quad . \quad . \quad . \quad \text{(ii)}$$

By a simple transformation the wave equation (i) then becomes :—

$$\frac{d^2\phi}{dt^2} = c^2\left(\frac{d^2\phi}{dr^2} + \frac{2}{r} \cdot \frac{d\phi}{dr}\right) \quad . \quad . \quad . \quad \text{(iii)}$$

But $$\frac{d^2\phi}{dr^2} + \frac{2}{r} \cdot \frac{d\phi}{dr} = \frac{1}{r} \cdot \frac{d^2(r\phi)}{dr^2}$$

and if $r$ is independent of $t$ we can write the wave equation in the form :—

$$\frac{d^2(r\phi)}{dt^2} = c^2 \, \frac{d^2(r\phi)}{dr^2} \quad . \quad . \quad . \quad . \quad \text{(iv)}$$

The solution of (iv) is :—

$$\phi = \frac{1}{r}\left\{F_1(r - ct) + F_2(r + ct)\right\} \quad . \quad . \quad \text{(v)}$$

where $F_1$ and $F_2$ are any single-valued functions of $r$ and $t$. This equation signifies a wave (or rather two waves) propagated from and towards the origin. When we are dealing with irrotational motion of fluids we can find a function called the *velocity potential* such that its space differential in any direction gives us the measure of the velocity of the fluid in that direction. This velocity-potential function must then satisfy the wave equation (i) or (iv). For a simple harmonic or sine-form wave this velocity potential $b$ for radial propagation from a centre takes the form :—

$$b = \frac{B}{4\pi} \cdot \frac{\cos(mr - \omega t)}{r} \quad . \quad . \quad . \quad \text{(vi)}$$

where $m = 2\pi/\lambda$ and $\omega = 2\pi/T$, $\lambda$ being the wave-length and $T$ the periodic time. The velocity of the fluid at the distance $r$ in the direction of $r$ is then given by $db/dr$.

If $a$ be the displacement of any particle of the fluid from its zero position then $da/dt$ (which may be written $\dot{a}$) is given by :—

$$\dot{a} = \frac{da}{dt} = \frac{db}{dr} = \frac{B}{4\pi r^2}\left\{\cos(mr - \omega t) + mr\sin(mr - \omega t)\right\} \quad \text{(vii)}$$

If we are considering air-wave motion or condensational waves, then Lord Rayleigh has shown in his "Treatise on Sound" (vol. 2, § 244, p. 14) that if $p$ is the variable part of the pressure and $\rho$ is the density of the air, the value of $p$ is given by $p = -\rho(db/dt)$. But from (v) we have

$$\frac{db}{dt} = -\frac{\omega B}{4\pi r}\sin(mr - \omega t) \quad . \quad . \quad \text{(viii)}$$

Also the energy $W$ conveyed in the direction of $r$ through unit of area in unit of time is the mean value of $p$ and $\dot{a}$ throughout one complete period. Hence from (vii) and (viii)

$$p\dot{a} = \frac{\rho\omega B^2}{16\pi^2 r^3}\left\{\sin(mr - \omega t)\cos(mr - \omega t) + mr\sin^2(mr - \omega t)\right\} \quad . \quad \text{(ix)}$$

The mean value of $\sin^2(mr - \omega t)$ throughout a period is $\frac{1}{2}$, and the mean value of the first term in the bracket of (ix) is zero.

Hence for the value of $W$ we have the expression :—

$$W = \frac{\rho\omega^2 B^2}{(4\pi r^2)(8\pi c)} \quad . \quad . \quad . \quad . \quad \text{(x)}$$

If we write $W_t$ for the whole energy sent out per unit of time through a spherical surface of radius $r$ described round the origin, we have $4\pi r^2 W = W_t$.

Hence $$W_t = \frac{\rho\omega^2 B^2}{8\pi c} \quad . \quad . \quad . \quad . \quad . \quad \text{(xi)}$$

Now from Equation (vii) it is seen that the maximum value of the velocity ($\dot{a}$) during a period, which may be denoted by $\dot{A}$, is given by :—

$$\dot{A} = \frac{B}{4\pi r^2}\sqrt{(1 + m^2 r^2)} \quad . \quad . \quad . \quad \text{(xii)}$$

Also we have $\dot{A} = A\omega$, where $A$ is the maximum value of the displacement $a$ during the period.

Therefore we have :—

$$\omega^2 B^2 = \frac{(4\pi r^2)^2 A^2 \omega^4}{1 + m^2 r^2} \quad . \quad . \quad . \quad \text{(xiii)}$$

and hence from (xi) and (xiii)

$$W_t = \frac{\rho}{8\pi c} \cdot \frac{(4\pi r^2)^2 A^2 \omega^4}{1 + m^2 r^2} \quad . \quad . \quad . \quad \text{(xiv)}$$

But the product $A(4\pi r^2) = V$ denotes the maximum quantity of the fluid moved across the surface of the enclosing sphere of radius $r$ by the wave motion. Accordingly we have, finally :—

$$W_t = \frac{\rho}{8\pi c} \cdot \frac{V^2\omega^4}{1 + m^2 r^2} \quad . \quad . \quad . \quad \text{(xv)}$$

There are then two cases to be considered : (1) when the distance $r$ is large compared with the wave-length $\lambda$ (where $m = 2\pi/\lambda$), and (2) when $r$ is small compared with $\lambda$. In the first case $mr$ and therefore $m^2r^2$ are large compared with unity. Then Equation (xv) reduces to :—

$$W_t = \frac{\rho}{8\pi c} \cdot \frac{V^2\omega^4}{m^2 r^2} \quad . \quad . \quad . \quad . \quad \text{(xvi)}$$

But $\omega^2/m^2 = c^2$, and $V^2 = A^2 16\pi^2 r^4$. Hence (xvi) becomes :—

$$W_t = \tfrac{1}{2}\rho c\omega^2 A^2 (4\pi r^2)$$

or (since $W_t = W4\pi r^2$)

$$W = \tfrac{1}{2}\rho c\omega^2 A^2 \quad . \quad . \quad . \quad . \quad \text{(xvii)}$$

This is the same expression as that for the energy passing through unit of area in unit of time in the case of a plane wave, and this is obviously correct because at very large distances the wave-front of the spherical wave becomes equivalent to a plane wave [see Equation (7) on page 614].

Then in the second case when $r$ is small compared with $\lambda$ we have $m^2r^2$ small compared with unity. The expression (14) then becomes :—

$$W_t = \frac{\rho}{8\pi c} \cdot \omega^4 V^2 \quad . \quad . \quad . \quad \text{(xviii)}$$

Now for air, $\rho = 0{\cdot}00129$ grammes per cm$^3$ and $c$ for sound waves $= 3{\cdot}3 \times 10^4$ cm per second. Also $\pi^3 = 31$, and

$$2\rho\pi^3/c = (0{\cdot}0026 \times 31)/(3{\cdot}3 \times 10^4) = 1/400\,000$$

Hence we have :—

$$W_t = \frac{n^4 V^2}{400\,000} \quad . \quad . \quad . \quad . \quad \text{(xix)}$$

This is the expression used in the text of the lecture in Equation (22) on page 621. In the case of a telephone, if we consider the energy passing through the surface of a sphere with radius small compared with mean wave-length of speech waves, which is, for a frequency of 800, about 40 cm, and if we consider that the quantity $V$ in the above formula (xix) is the volume included between the surfaces of the diaphragm in its two extreme positions, then (xix) approximately applies and gives us the total energy emitted per second as speech-wave energy by the receiver. The ideal method of measuring the acoustic efficiency of a telephone receiver would be to measure the electric power given to it at a certain frequency and constant current by means of a wattmeter, (*a*) when the telephone was emitting sound waves, and (*b*) when the receiver was enclosed in a vessel exhausted of its air so that no sound waves could be produced. If the electric current was adjusted to be the same in both cases, the ratio of the readings of the wattmeter would give the efficiency. No wattmeter yet made is sufficiently sensitive to carry out this experiment with accuracy.

## APPENDIX II.

The following statistics relating to telephone circuits and plant in the United States and in Great Britain have been supplied by the kindness of the President, Mr. F. Gill, for the United States, and by Colonel T. F. Purves, O.B.E., Engineer-in-Chief of the British General Post Office, for Great Britain. They are valid up to the end of 1922.

### I. STATISTICS RELATING TO TELEPHONE PLANT IN THE UNITED STATES OWNED BY THE LONG LINES DEPARTMENT AND ASSOCIATED COMPANIES.

| Item No. | Type of Plant | Miles |
|---|---|---|
| 1 | Miles of aerial wire loaded with side-circuit loading coils .. .. | 346 000 |
| 2 | Miles of aerial wire in phantom circuits loaded with coils .. | 288 000 |
| 3 | Miles of wire in cables loaded with side-circuit coils .. .. .. | 450 000 |
| 4 | Miles of wire in cables loaded with phantom-circuit coils .. .. | 290 000 |
| 5 | Through line repeaters .. .. | 2 070 |
| 6 | Cord circuit repeaters .. .. | 400 |
| 7 | 4-wire repeaters .. .. .. | 440 |
| 8 | Repeater stations .. .. .. | 220 |

*Note* :—Items 1 and 2 and 3 and 4 are not additive because the same wires form side and phantom circuits. Reckoned in miles of circuit the data are as follows :—

| | |
|---|---|
| (1) Miles of physical circuit in aerial wires forming side circuits, loaded with coils .. | 172 000 |
| (2) Miles of phantom circuit in aerial wires on which loading coils are used .. .. | 72 000 |
| (3) Miles of physical circuit in cables on which loading coils are used .. .. .. | 225 000 |
| (4) Miles of phantom circuit in cables on which loading coils are used .. .. .. | 725 000 |

### II. STATISTICS RELATING TO TELEPHONE CIRCUITS IN GREAT BRITAIN CONTROLLED BY THE BRITISH POST OFFICE.

| Item No. | Type of Plant | Miles |
|---|---|---|
| 1 | Miles of aerial telephone circuit in which the physical or side circuits are equipped with loading coils.. | 800* |
| 2 | Miles of side circuit which are coil-loaded in underground cables, completed .. .. .. .. | 156 000† |
| | Ditto, in progress .. .. .. | 102 000 |
| 3 | Miles of phantom circuit in underground cables which are coil-loaded, completed .. .. .. .. | 27 000 |
| | Ditto, in progress .. .. .. | 41 600 |
| 4 | Total number of loading coils installed, completed .. .. .. | 83 500 |
| | Ditto, in circuits in progress .. | 102 500 |

(5) There are at present 13 telephone repeater stations equipped with thermionic repeaters in operation, 8 in course of construction, and 4 to be begun in 1923. These stations are at :—

Glasgow
Leeds
Manchester
Derby
Fenny Stratford
Birmingham
Bristol
Leicester
London
Dover
Carlisle
Shrewsbury
Morfa Nevin
Taplow
Marlborough
Guildford
Ipswich
Aldeburgh
Newport
Gloucester
Canterbury
Catterick
Newcastle
Edinburgh
Jedburgh

(6) The British Post Office has at present 16 automatic telephone exchanges in public service, having a

---

* This small amount of aerial line loading is due partly to the unsuitable climatic conditions of this country, which make aerial line loading difficult or disadvantageous, and to the fact that the longest present aerial lines in a country so small as Great Britain are fully efficient when unloaded. It is also due partly to the intention to replace as soon as possible aerial trunk lines by underground cables loaded and equipped with repeaters.

† The percentage of underground telephone cable mileage to total wire mileage in Great Britain is considerably greater than in any other country. All underground circuits, both physical and phantom, are now loaded. This is due to the policy, intentionally pursued, of late years of placing all important trunk-line telephone circuits underground as soon as possible.

total capacity for 30 000 subscribers. There are also 6 more in progress having a capacity for 11 000 lines. Six systems are represented, viz.:—

The Automatic Telephone Manufacturing Co., Ltd.
Siemens Brothers and Co., Ltd.
The Western Electric Co., Ltd.
The Relay Automatic Telephone Co., Ltd.
The General Electric Co., Ltd., and
The Lorimer Automatic Co., of Canada.

The use of automatic exchanges for large public and private establishments is greatly increasing, such as the Bank of England, the London County Council Hall, etc. The public exchanges vary from large ones such as Leeds with a capacity of 15 000 lines to small exchanges such as Chepstowe with 100 lines. It is thus clear that the British Government telephone service is, as regards all recent advances in telephonic inventions, well to the front in its adoption of them.

---

# PERMANENT MAGNETS, AND THE RELATION OF THEIR PROPERTIES TO THE CONSTITUTION OF MAGNET STEELS.*

By E. A. Watson, Associate Member.

(*Paper received* 31*st October*, 1922.)

## SUMMARY.

The first portion of the paper deals with the properties required in a permanent magnet. It is shown that in all cases, provided the magnet is properly proportioned to its work, the true criterion is the $(BH)_{max.}$ value. The relationship existing between the values of saturation density, remanent density, coercive force and $(BH)_{max.}$ is then considered, and a modified form of Kennelly's or Lamont's law is developed, which enables this relationship to be expressed both analytically and graphically. It is shown that in actual practice magnets of homogeneous composition obey this law very closely indeed.

The paper next deals with the case of magnets which are microscopically not of uniform composition, and which contain two principal constituents. The relation between the magnetic properties of the magnet and the grouping of the constituents is considered, in addition to its relation to their magnetic properties. The constituents may fall under three headings: (*a*) non-magnetic, (*b*) magnetic and possessed of high coercive force (magnetically hard), and (*c*) magnetically soft, i.e. magnetic but of low coercive force. Evidence shows that the highest values of $(BH)_{max.}$ are obtained when the magnet consists uniformly of a material of class (*b*), and that with the right steels and appropriate heat treatment other constituents are absent. The constituent in question is, however, only a transition product between the other two classes (*a*) and (*c*), and its presence in the pure state is therefore not always easy of attainment.

Data taken chiefly from modern cobalt steels are given in support of the theories put forward, and some suggestions are made for further research and development work in this connection.

## Part I.

While the determination of magnetic flux in a circuit comprising a permanent magnet is subject to the well-known and generally understood laws of magnetic induction, it was not until Mr. Evershed's recent paper * that the subject of the design and calculation of such circuits was put on a satisfactory basis comparable with the position of the more generally used circuits in which an electromagnet provides the necessary magnetomotive force. Mr. Evershed's treatment of the subject is so comprehensive that it is felt that but little can be added to it. At the same time, as the theoretical work on which this paper is based was in the main done prior to the publication of his paper, and as the subject has been approached somewhat differently, it is felt that a short description of the lines of reasoning involved may not be out of place.

A permanent magnet may be treated as a seat of magnetomotive force possessed also of a reluctance which is not a constant, but varies with the flux linked with the magnet, the reluctance further depending not only on the flux linked at any moment but on the previous history of the magnet up to the point of establishment of the flux.

For any given flux linking the magnet there will always be a certain proportion of the total magnetomotive force which is used up in driving the lines through the magnet itself, the remainder being available for maintaining the flux in the external circuit.

The relation between the flux linking the magnet and the magnetomotive force available for use in the external circuit is best expressed by the well-known *BH* curve of the steel, forming a small section of the hysteresis loop between the positive *B* and negative *H* axes. For any point on this curve the ordinate of *B* represents the flux density in the magnet, while the abscissa *H* represents the demagnetizing force necessary to reduce the density to this point. If, therefore, the conditions throughout the length of the magnet are constant, the product $Hl$, where $l$ is the length of the magnet, gives the M.M.F. available in the external circuit, while the product $BA$, where $A$ is the area of the magnet, will give the total flux linking the magnet, which is equal to the sum of the useful flux in the external circuit and the leakage flux between the extremities of the magnet and other parts of the circuit.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* "Permanent Magnets in Theory and Practice," *Journal I.E.E.*, 1920, vol. 58, p. 780.

If $\theta$ the total flux required and $M$ the total M.M.F. are both fixed by the design of the instrument in connection with which the magnet is to be employed, we have:—

$$\text{Volume of steel in magnet} = \frac{\theta}{B} \times \frac{M}{H}$$

and this will clearly be a minimum when *BH* is a maximum, so that to make the best use of the steel the magnet must be worked at the point at which *BH* has a maximum value.

We have now to determine at what point the magnet fitted to an instrument of any kind is normally working, and, in the case of instruments such as magnetos, in which the working condition is cyclical, what relation the normal working point should bear to the extreme conditions of service.

The *BH* curve as usually given for a magnet is that obtained when the flux in the magnet has been pushed to its saturation value, and the magnetizing force then removed. It is, of course, only one of an infinite series of curves forming portions of loops between different maximum values of *B* and *H*. The *BH* curve is, moreover, irreversible, and holds only when *H* increases negatively from *O* to $-H$. It is obviously useless to design a magnet to work normally at the point $B_1H_1$ (see Fig. 1) when occasional overloads or extreme conditions of service may bring about the conditions denoted by $B_2H_2$.

Consider first the case of a magnet in a meter, or similar class of apparatus, in which the conditions of service are reasonably constant but in which it is important that any momentary variation in magnetic conditions, such as that due to a heavy overload, the presence of stray fields, or a severe mechanical vibration, shall not affect its accuracy.

It is clear that the normal working point of the magnet must lie on a reversible cycle, and that the length over which the cycle is truly reversible must exceed the variation in conditions which may be met with in practice.

If starting at any point, such as $H_2$ in Fig. 1, we increase *H* positively, or in other words reduce the demagnetizing force applied to the magnet, the condition will be represented not by the original *BH* curve, but by another one starting from the point $B_2H_2$ and much less steeply inclined to the axis of *H* than the original one. This curve, if carried far enough for positively increasing values of *H*, ultimately bends upwards, and joins the *BH* loop at the point of saturation. This curve really forms portion of a subsidiary hysteresis loop, which is described if the material is taken to any point to the right of $H_2$, and then back again to $H_2$ itself. For values of *H* between $H_2$ and zero, the width of this loop is, however, very narrow, so that the cycle is very nearly reversible. If now we choose our working point on this subsidiary loop at, say, the point $B_3H_1$ in Fig. 1, then, provided any disturbing influence or momentary overload never causes the value of *H* to exceed $H_2$, on the removal of the overload the point $B_3H_1$ will be resumed, and the accuracy of the instrument will be unaffected. In the same way, if the disturbing influence is such as to strengthen the magnet, the change in magnetic condition will be only slight, corresponding in fact to the breadth of the subsidiary loop.

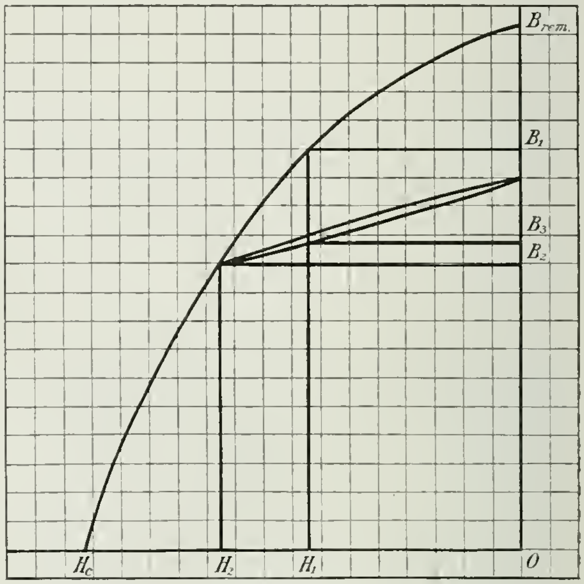


Fig. 1.—Typical main and subsidiary *BH* loops.

In the case of an instrument subjected to known electrical overloads the location of the working point with respect to the *BH* curve is a matter of calculation, although it would appear that some research is necessary in order to determine what allowance is necessary to cover the effect of mechanical vibration and changes of temperature.

The case of a magneto in which the magnet is subjected to a rapidly repeated series of cyclic changes has been dealt with in a previous paper. Here energy is continually being stored in the field provided by the magnet, and then transferred to the electric circuit. In an ideal magneto the energy stored in each cycle would vary between the values of zero, when the armature is in the position of maximum induction, and a maximum when the flux is distorted to the position corresponding to maximum energy storage. The energy which the magnet is sustaining in the external circuit is proportional to the product of $\phi$ the total flux and $M$ the magnetomotive force associated with it, and is equal to $M\phi/8\pi$, or, writing $M$ as $Hl$ and $\phi$ as $BA$ we have :—

Energy stored in distorted field

$$= \frac{BH}{8\pi} \times \text{volume of magnet}$$

Owing to the peculiar construction of the ordinary magneto the total energy storage is twice this amount, the field being distorted simultaneously at two points, so that the total energy storage becomes

$$\frac{BH}{4\pi} \times \text{volume}$$

Here again the condition of maximum output, which is the same as maximum energy storage, becomes simply that of maximum $BH$. In an actual magneto the conditions are not, of course, strictly the same as in the ideal case. In particular the reluctance of the flux path never falls to zero, and in most cases seldom falls much below 20 per cent of the value when the energy storage is a maximum. Fig. 2 represents the conditions in an actual machine. In this case the flux measurements were made by search coils on the magnet, and the values for the M.M.F. were obtained by means of a Chattock magnetic potentiometer, a most useful although little-known instrument, of which extensive use has been made in connection with this work.

Fig. 2 shows :—

(1) The point at which the magnet is working immediately after magnetization. This point $P_1$ is simply that at which the armature magnetization curve and the $BH$ curve of the magnet intersect.

(2) The working range of the magnet when the armature is slowly revolved with the windings on open-circuit, the changes in reluctance being merely those due to the configuration of the armature and pole-shoes.

(3) The working range when the armature is removed from the tunnel and replaced.

(4) The working range when the armature is short-circuited at a high speed. This is equivalent to (3) above, except that the space occupied by the armature may be regarded as being replaced by a medium with a permeability less than unity. Consequently the conditions are still more severe than in the case when the armature is withdrawn. In order to render the figures comparable without regard to the dimensions of the machine investigated, they have been reduced to values of $B$ and $H$ instead of total flux and magnetomotive force. The design in question was one employing cobalt steel, hence the large values of $H$ involved, although these figures, being mean values taken over the total length of the magnet, are in the particular machine investigated about 15 per cent less than the maximum values in the centre of the magnet itself, the difference being due to the leakage which occurs towards the ends of the magnet and the point of contact between the magnet and pole-shoes.

The points $P_1$, $P_2$, $P_3$ and $P_4$ are the points of intersection of lines representing the reluctance of the path traversed by the flux outside the magnet itself and the $BH$ curve for the magnet. For the magnet to be used to the best advantage the point which corresponds to the most severe condition of normal working should coincide with the point on the curve for which $BH$ is a maximum, and hence if the length and section of the magnet are known we can obtain a definite relation of $B_{rem.}$ to $H_c$. In the case of magnetos the occasion is bound to arise at some period when the armature is short-circuited while running at a high speed, so that

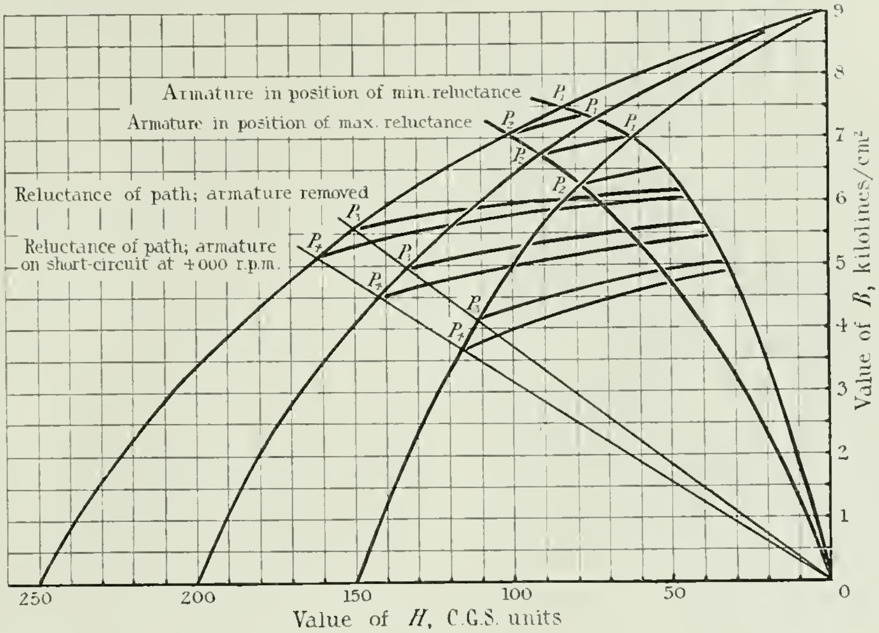


FIG. 2.—Working range of magneto magnets. Same remanence values of $H_c$.

the point $P_4$ should be made that corresponding to $(BH)_{max.}$ A design in which $P_4$ lies appreciably to the left of the $(BH)_{max.}$ point will give good performance under easy conditions of service, but is almost certain to fall off after long periods of service under varied conditions.

*Relations between $B_{rem.}$, $H_c$ and $(BH)_{max.}$*—From the foregoing it is clear that in order to obtain a simple method of proportioning a magnet it is very desirable that we should be able to express the relation between the quantities involved otherwise than by the use of a graph on squared paper. Fortunately it is possible to obtain such a relation, which, although it may not be absolutely correct, appears to be well within the limits of error which can be tolerated in ordinary commercial design. The relation is based on Lamont's law of magnetizability, further developed by Dr. Kennelly, Prof. Crapper and the present author.

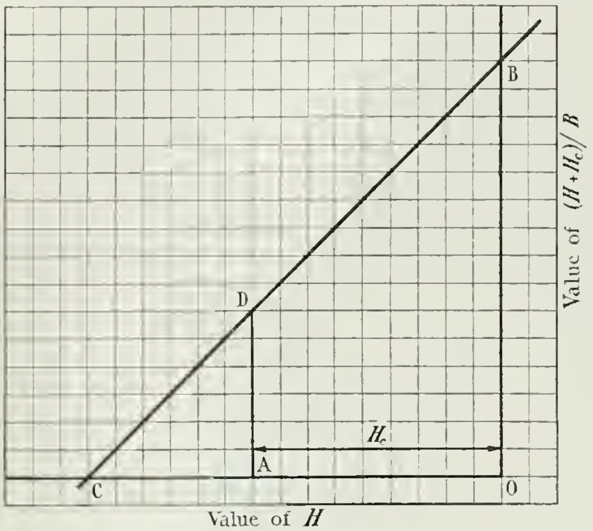


FIG. 3.—Lamont's law as modified for material of high coercive force.

Lamont's law may be stated thus: The permeability of a steel is proportional to the difference between the saturation density of the steel and the density at the point under consideration, or

$$\mu = k(B_s - B) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Writing $\mu = B/H$ this gives us

$$\frac{H}{B} = a + bH \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $b = 1/B_s$ and $a$ is the slope of the curve at the point $H = 0$.

Kennelly has pointed out that Lamont's law only holds strictly when we consider $B$ as the magnetization of the iron alone, and not that as normally read, i.e. it is the ferro-magnetic density $B_i$ which is equal to $(B - H)$. Consequently, in all that follows, when we refer to $B$ we shall regard it as the true induction in the iron itself which is being considered. $B_s$, the saturation density, has then a definite value and can with certain precautions be readily measured. Further, in all the curves given in the paper the values of $B$ given are the true ferro-magnetic induction, and not the total induction in the magnet. These values were readily obtained by a special testing gear, particulars of which are given in an appendix.

An alternative statement of Lamont's law is to say that $\mu$ (i.e. $B/H$) bears a linear relation to $B$, or that $H/B$ bears a linear relation to $H$. This can easily be tested for any steel by plotting either $\mu$ against $B$ or $1/\mu$ against $H$, when the points obtained should, if the law be true, fall on a straight line.

In the case of any steel initially free from magnetism it will be found that the law only holds to any extent when the point of inflexion, which occurs in the early part of the curve, has been passed, and the greater the coercive force of the steel, and the more pronounced the point of inflexion, the larger is the region over which the law breaks down.

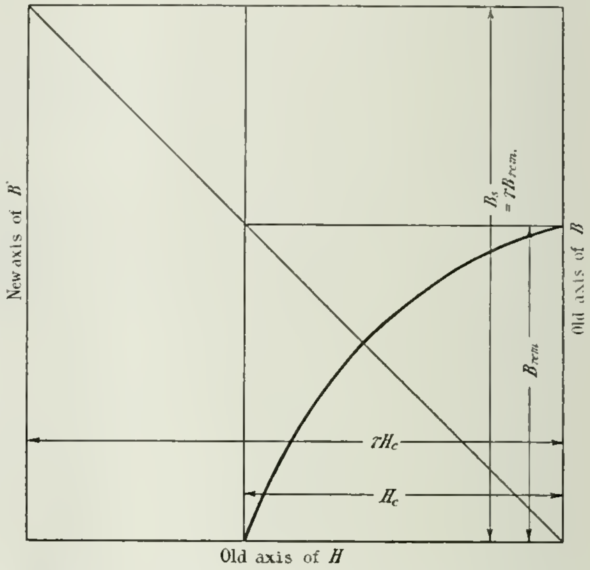


FIG. 4.—*BH* curve referred to pair of conjugate axes, showing hyperbolic character.

The ordinary statement of Lamont's law does not, therefore, hold for a magnet steel taken from an initially unmagnetized condition up to the saturation point. An inspection of the portion of the $BH$ loop between the points of $B_s$ and $B = 0$, $H = -H_c$ discloses a very marked resemblance to the magnetization curve, with the exception that the point of inflexion is absent, and we might therefore expect that this portion of the curve would obey a similar law, behaving in fact as a curve subject to the law, but displaced through the distance $H_c$. Lamont's equation for such a displaced curve would be :—

$$(H + H_c)/B = a + b(H + H_c) \quad . \quad . \quad (3)$$

where $a$ is the slope of the curve at the point $H = H_c$ and $b$ is equal to $1/B_s$.

On Fig. 3 is drawn the straight line represented by this equation, the values of $(H + H_c)/B$ being plotted against the values of $H$, while Fig. 4 gives the corresponding $BH$ curve. The straight line $(H + H_c)/B$ cuts the axis $H = 0$ at the point B, and $OB = H_c/B_{rem.}$

At the point $H = 0$ we obtain from the equation

$$\frac{H_c}{B_{rem.}} = a + \frac{H_c}{B_s}$$

$$a = \frac{H_c(B_s - B_{rem.})}{B_s B_{rem.}} = \frac{H_c}{B_{rem.}} \cdot \frac{B_s - B_{rem.}}{B_s}$$

$$= \mathrm{OB} \cdot \frac{B_s - B_{rem.}}{B_s}$$

In Fig. 3, AD, the ordinate at the point $H = -H_c$ is equal to $a$, since $(H + H_c) = 0$.

Hence $\mathrm{AD} = \mathrm{OB}\,\dfrac{B_s - B_{rem.}}{B_s}$.

Produce BD to cut OA in C. Then :—

$$\frac{\mathrm{OC}}{\mathrm{OA}} = \frac{\mathrm{OB}}{\mathrm{OB} - \mathrm{AD}} = \frac{1}{1 - \dfrac{B_s - B_{rem.}}{B_s}} = \frac{B_s}{B_{rem.}}$$

Let us denote the ratio of $B_s$ to $B_{rem.}$, i.e. of saturation to remanent density, by $r$. Then $\mathrm{OC} = rH_c$.

$$a = \frac{H_c}{B_{rem.}} \cdot \frac{r-1}{r}$$

$$\frac{H + H_c}{B} = \frac{H_c}{B_{rem.}} \cdot \frac{r-1}{r} + \frac{H + H_c}{B_s}$$

$$= \frac{H_c(r-1)}{B_s} + \frac{H + H_c}{B_s} \quad . \quad . \quad (4)$$

which is the equivalent form of the equation in terms of the three quantities $H_c$, $B_{rem.}$ and $B_s$, which can be readily measured. This form is therefore preferable to that involving $a$, the slope of a curve at a particular point.

$$(H + H_c) \cdot \frac{B_s - B}{B_s B} = \frac{H_c(r-1)}{B_s}$$

$$\frac{H + H_c}{B}(B_s - B) = H_c(r - 1)$$

Refer the equation to a pair of axes through the points $H = -rH_c$ and $B = 0$, and $H = 0$, $B = B_s$, i.e. write $B = (B_s - B')$ and $-H = (rH_c - H')$. Then

$$\frac{[H' + H_c(1 - r)]B'}{B_s - B'} = H_c(r - 1)$$

$$B'H' + B'H_c(1 - r) = B_sH_c(r - 1) - B'H_c(r - 1)$$

$$B'H' = B_sH_c(r - 1)$$

$$= \text{constant} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

This is the equation of a hyperbola, hence the curve is a portion of a hyperbola lying between the new axes chosen through the points $B_s$ and $-rH_c$.

*Evaluation of* $(BH)_{max.}$—Since $B = (B_s - B')$ and $H = (H' - rH_c)$, we have

$$BH = (B_s - B')(H' - rH_c)$$

Differentiating with respect to $H'$ and equating to zero gives

$$0 = -\frac{dB'}{dH'}(H' - rH_c) + B_s - B' \quad . \quad . \quad (6)$$

From Equation (5) we obtain, by differentiation,

$$\frac{dB'}{dH'} = -\frac{B_sH_c(r-1)}{(H')^2}$$

and, by substituting in (6), we obtain

$$0 = \frac{B_sH_c(r-1)(H' - rH_c)}{(H')^2} + B_s - B'$$

$$= \frac{B_sH_c(r-1)}{H'} - \frac{B_sH_c(r-1)rH_c}{(H')^2} + B_s - B'$$

$$= B_s\left[1 - \frac{H_c^2 r(r-1)}{(H')^2}\right]$$

Also $\qquad H' = H_c\sqrt{[r(r-1)]} \quad . \quad . \quad . \quad . \quad (7)$

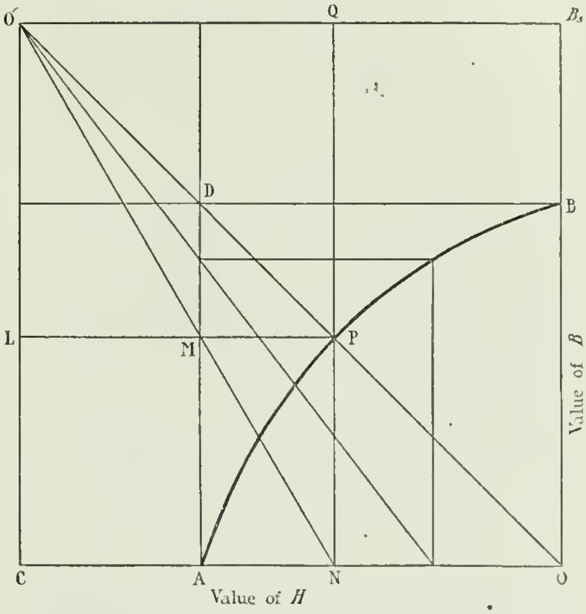


FIG. 5.—Graphical construction for point of $(BH)_{max.}$, and construction of $BH$ curve.

Whence from (5) we obtain

$$B' = B_s\frac{r-1}{\sqrt{[r(r-1)]}} \quad . \quad . \quad . \quad . \quad (8)$$

The corresponding values of $B$ and $H$ on the original axes are found to be :—

$$H = H_c[\sqrt{\{r(r-1)\}} - r]$$

$$B = \frac{B_s}{r}[r - \sqrt{\{r(r-1)\}}]$$

$$BH = B_sH_c[2\sqrt{\{r(r-1)\}} - 2r + 1]$$

The algebraic expression for $(BH)_{max.}$ is thus somewhat complicated, but fortunately a very simple graphical construction can be found which will enable the calculation to be avoided.

Writing

$$\frac{B}{H} = \frac{B_s[r - \sqrt{\{r(r-1)\}}]}{rH_c[\sqrt{\{[r(r-1)\}} - r]} = -\frac{B_s}{rH_c} = -\frac{B_{rem.}}{H_c} \qquad (9)$$

we see that the point of $(BH)_{max.}$ must lie on a straight line passing through the origin and the point $B = B_{rem.}$, $H = -H_c$. The intersection, therefore, of this line with the $BH$ curve will at once give the point of $(BH)_{max.}$

The foregoing relations further enable us to obtain a very simple graphical construction for the $BH$ loop. This construction, due in the first place to Dr. D. K. Morris, and shown in Fig. 5, is as follows: From O′, the origin of the new system of axes, and the point $B = B_s$, $H = -rH_c$ on the old one, draw a series of sloping lines to cut the ordinate in points M and the axis of $H$ in point N. Draw perpendiculars to these axes to meet in P. Then P is a point on the curve. For we see from inspection that:

$$H' = \mathrm{PL} = \mathrm{O'C} \tan \mathrm{CO'N} = B_s \tan \mathrm{CO'N}$$

$$B' = \mathrm{PQ} = \mathrm{ML} \cot \mathrm{CO'N} = H_c(r-1) \cot \mathrm{CO'N}$$

Hence $B'H' = B_sH_c(r-1)$, which is the equation to the curve.

## Part 2.

In the foregoing we have developed a construction which, if Lamont's modified law is correct, should enable us to predict the $BH$ curve for a magnet when only three points are known, in just the same way that a circle is determined when three points on it are given. It now remains to be seen how closely this construction holds in practice, and to what extent our conclusions can be applied to actual magnets.

In attempting to verify them we may follow several different courses. The most extreme probably is to determine by actual measurement the values of $B_s$, $B_{rem.}$ and $H_c$ for a magnet, to construct the curve from these, and see how far it agrees with the curve actually observed. This is naturally rather a severe test. In the first place the value of $B_s$ is not easy to measure accurately, and in the second place it would be expected that if the law breaks down at all it will be when pushed to extremes, such as is represented by the point $B = B_s$.

As a matter of fact, fairly close agreement is sometimes obtained when the curve is constructed from these three determinants, but only in cases when the microstructure of the magnet shows exceeding uniformity, and in most cases considerable discrepancies become apparent.

Another method of checking the law which does not involve its holding over such an extreme range as the foregoing is to calculate or determine graphically an artificial value of $B_s$ from three points which can be easily measured accurately, say the points $B_{rem.}$, $H_c$ and an intermediate one, such as $(BH)_{max.}$. From the artificial value of $B_s$ thus obtained a curve can be constructed which can be compared with the observed one. This usually gives very close agreement indeed. If desired, this artificial value of $B_s$ can be compared with the figure obtained by actual measurement.

An alternative but equivalent method to the foregoing is to reverse the graphical construction given for drawing the curve when the point O′ is known. Referring to Fig. 5 we see that if the curve is found by experiment, and perpendiculars from various points on it are drawn to the axis of $H$ and the perpendicular through the point $H = -H_c$, the diagonal lines, such as MN, should all meet in a point O. This check is easily carried out in practice. In most cases a very close agreement is found, the points of intersection of the diagonals all being coincident.

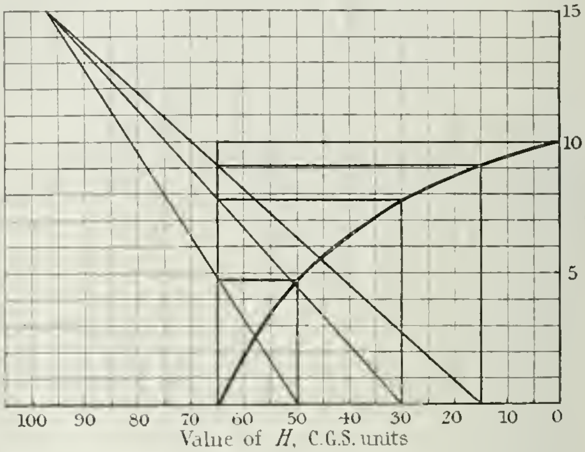


FIG. 6.—Graphical construction for $BH$ curve. Typical tungsten steel.

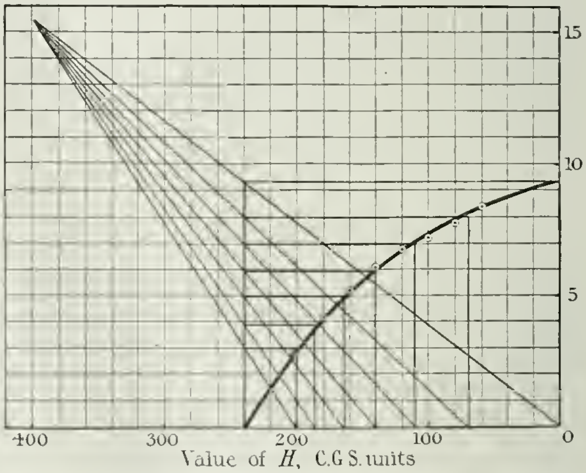


FIG. 7.—$BH$ loop for typical cobalt steel, correctly hardened. Estimated and observed value of $B_s$ coincident.

For example, Fig. 6 shows this construction as applied to a typical case of a tungsten-steel magnet, while in Fig. 7 is shown the curve obtained for a correctly hardened cobalt-steel magnet, and also the points obtained by construction from the observed values of $B_s$, $B_{rem.}$ and $H_c$. In this case the circles mark the actual observed points on the $BH$ loop, as found by experiment, and it will be seen that they agree very closely with the points determined by graphical construction.

In the course of the past three years the author has had occasion to examine the *BH* loops of many hundreds of magnets, and frequent occasions have been taken to check the accuracy of Lamont's law. Although in many cases good agreement, such as is shown in Figs. 6 and 7, has been obtained, in others there has been considerable divergence, and generally speaking it has been noticed that the magnets which showed the greatest divergence were those which were magnetically poor. This seemed to suggest that although the properties of a homogeneous magnetic material might be represented in the manner outlined, yet in many cases an actual magnet behaved, not as a homogeneous material, but as a mixture of constituents of different magnetic properties, all of which contributed to the final result. Further, since the best magnets showed the closest agreement to theory it appeared that there was in every case some one constituent which should form the whole of the magnet, and it was clearly of importance to determine, if possible, what this constituent was, and also to find, if possible, the conditions under which this constituent was formed to the exclusion of others of inferior magnetic properties.

The next section of the paper, therefore, is a consideration of the possible constituents which may be present in a magnet steel, and the way in which the properties of the magnet may depend not only upon their several properties and proportions but also upon the manner of their occurrence and relative grouping.

In setting forth his ideas the author has used to a large extent the language of the allotropic theory, not that he is necessarily a supporter of this theory, but because it forms a convenient way of expressing the changes which occur when carbon passes out of solution in a magnet steel. Whether, however, this passing out of solution is accompanied by any allotropic change in the iron itself he will leave for the metallurgists to solve.

## Part 3.

The metallurgical aspect of the constitution of a permanent magnet is a subject which has received but scanty attention. In all probability considerable unpublished work has been done upon it by various firms engaged in the manufacture of magnets, but the results obtained appear to have been regarded as a trade secret, and no publication or discussion of them has taken place. It is, in fact, safe to say that there is no general agreement among metallurgists as to what is the source from which a permanent magnet derives its properties. It is generally agreed that the power of retentivity, i.e. the coercive force, is a function of the amount of carbon intimately associated with the steel, but as to the exact nature of the association no definite pronouncement has been made, nor has any agreement been arrived at. There is no doubt whatever that the carbon, probably in the form of carbide, is in very intimate if not in molecular association with the iron, but on the other hand it is generally accepted that iron in the form in which it can dissolve carbon is non-magnetic, and that in the ordinary magnetic condition its power of dissolving carbon is practically nil. According to the allotropic theory, which is widely if not universally held, the power of iron to dissolve the carbide is associated with a particular allotropic form, generally denoted as the $\gamma$ condition, which in the ordinary case is stable only at high temperatures. The allotropic form which is possessed of the usual ferromagnetic properties is the $\alpha$ condition, which is normally stable at low temperatures. Between the $\alpha$ magnetic condition and the $\gamma$ non-magnetic condition there is, according to many authorities, an intermediate $\beta$ condition, in which the iron probably has a certain amount of dissolving power for carbon, but here again its magnetic properties would appear to be very feeble, if not altogether non-existent. The carbide of iron, $FeC_3$, has in itself very appreciable magnetic properties and is possessed of considerable coercive force, so much so in fact that the coercive force of an annealed steel appears to be chiefly, if not wholly, due to the carbide particles which have separated from the mass, but the properties of a permanent magnet cannot be explained by a mere mechanical admixture of carbide with pure iron, no matter how finely divided.

*List of constituents.*—It will be as well at this stage to enumerate the various constituents which may occur in a hardened magnet, together with a definition of each of these. It is believed that the definitions given are in general agreement with modern metallurgical practice, although there is some difference of opinion in regard to certain of them.

(1) *Austenite.*—Non-magnetic. Undecomposed solid solution of carbide of iron in iron. Normally stable only above the $AR_1$ point, but capable of retention at atmospheric temperature under special conditions.

(2) *Martensite.*—Magnetic. The first stage in the decomposition of austenite as defined above. Its properties depend upon the carbon content. With a sufficiently high carbon content it is intensely hard and possesses high coercive force. It is unstable and can only be retained at ordinary temperatures if the rate of cooling through the range of the normal change-point has been sufficiently rapid.

(3) *Troostite.*—The decomposition product immediately subsequent to martensite, and in which the iron has completely passed into the alpha or magnetic condition. The carbide is still in extremely intimate association with the iron.

(4) *Sorbite.* (5) *Pearlite.*—Successive further stages in the decomposition in which the ferrite and cementite definitely separate out from the mass. There is no hard and fast distinction between the two. In sorbite the ferrite and cementite particles are ultra-microscopic, while in pearlite they are capable of resolution. The magnetic properties are those of a mechanical admixture of ferrite and cementite.

*Consideration of constituents required in a permanent magnet.*—Let us imagine a piece of steel originally in the austenitic state to pass progressively through the stages just enumerated, and let us endeavour to follow the changes, magnetic and otherwise, which will occur. In the austenitic state the material is perfectly non-magnetic. The microstructure (Fig. 8) shows a mass of polygonal grains, each grain being in itself structureless. On passing to the martensitic state there will be a very distinct evolution of heat, a considerable expansion in volume, and a change in the microstructure. The former will show itself by a recalescence point (the $AR_1$ point) in the cooling curve, and the expansion in volume (from 0·5 to 1 per cent) can easily be measured. The polygonal grains develop an internal structure, which gives rise to characteristic markings (well seen in Fig. 9). If the change is due merely to the passage of the iron from the $\gamma$ to the $\beta$ state the material should still be non-magnetic, but if, on the other hand, $\beta$ iron is non-existent and the change is due to the formation of $\alpha$ iron, magnetic properties should appear. As a matter of fact all steels yet observed in the martensitic state show magnetic properties, although in many cases these are only feeble. What magnetic properties the martensitic material possesses must clearly be due to the presence of $\alpha$ iron, and if it can be proved that the evolution of heat and change of volume occur definitely before the assumption of the magnetic state it would appear that the supporters of the $\beta$ iron theory have a very strong case.

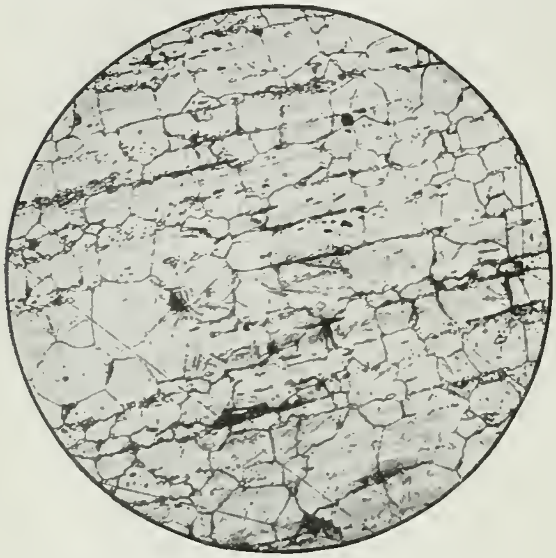


FIG. 8.—Typical austenitic structure. Magnification: 150 diameters.

The author has made several attempts to determine whether in the case of permanent magnet steels it is possible to obtain the volume-change and heat evolution which accompanies the $\gamma$–$\beta$ transformation without the appearance of magnetic properties. So far, however, the results have been negative, and it would appear that in a magnet steel the saturation density is proportional to the extent of the volume-change, and also of the heat evolution which has occurred in passing from the $\gamma$ state. This has been generally recognized by most workers, and the theory has been suggested that $\beta$ iron may exist in two states, the non-magnetic state stable only at high temperatures, and the magnetic state which can exist at ordinary temperatures. On this basis the intense mechanical hardness of a permanent magnet may be explained by the presence of $\beta$ iron, while at the same time its relatively high saturation density may be satisfactorily accounted for.

If, on the other hand, we consider that the iron in a permanent magnet is in the $\alpha$ condition and has consequently no dissolving power for carbon, yet the distribution of the carbide is so intimate that it is able to affect the properties of the iron itself, with the result that the properties are no longer those of a mechanical admixture of iron and carbide, nor yet of $\gamma$ iron containing carbide in solution, but are those of a totally distinct material.

There is at the present time a tendency to treat the condition of the carbide in a hardened steel as being in many ways akin to a colloidal solution, and it would appear that this analogy gives a very clear representation of the condition of the material in a hardened permanent magnet. It is naturally difficult to make a statement which will apply equally to both theories, but the author believes that the following expression of his views will be equally acceptable to both the $\beta$ and the $\alpha$ partisans.

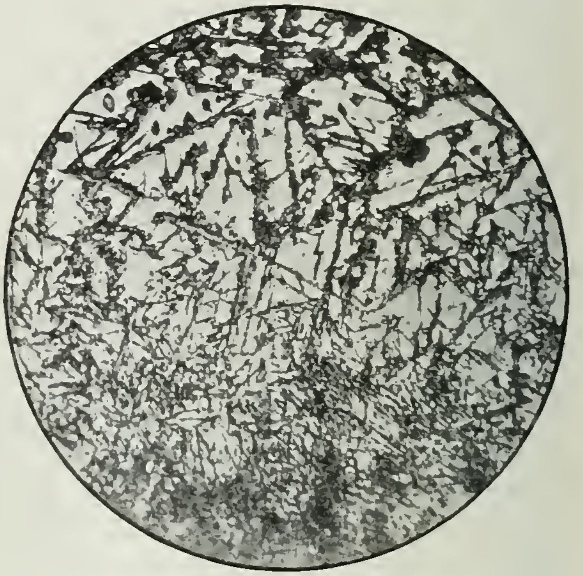


FIG. 9.—Partially transformed austenite, showing characteristic martensitic markings. Magnification: 150 diameters.

(1) In a correctly hardened magnet steel the non-magnetic $\gamma$ iron must be completely transformed, or, as an alternative statement, if the allotropic theory is not accepted the austenitic solid solution must be completely broken up.

(2) No segregation of the carbides and ferrite must be permitted to take place, or, in other words, the normal carbon change generally associated with the $AR_3$ point must be completely suppressed.

Now although, as indicated, the perfect magnet should consist entirely of one constituent only complying with the foregoing definition, in many cases other constituents may be present, and it is proposed to consider what will be the properties of magnets containing other constituents besides the ideal one. It may even be that the laws governing the states of equilibrium of the various constituents preclude the possibility of obtaining any one in the complete absence of the others.

*Relation of magnetic properties to structure.*—Certain properties of a magnet may depend in the case of a non-homogeneous material both upon the properties of the various constituents and also upon the method of grouping. Other properties may depend upon the relative amounts of the constituents and their properties, but may be independent of the way in which the constituents are grouped. The problem is therefore a complicated one, and in order to simplify it as far as possible we shall consider the following magnetic properties only :—

(*a*) Saturation density.
(*b*) Coercive force.
(*c*) Remanence.
(*d*) $(BH)_{max.}$

We shall consider first the presence of two constituents only, viz. a non-magnetic $\gamma$ constituent, for which all the properties above named are zero, and a magnetic constituent for which they have a definite value.

We shall, for the sake of convenience, denote these as the $\gamma$ and $\beta$ constituents, but, as before mentioned, without in any way committing ourselves to the allotropic theory, or identifying the latter with the presence of $B$ iron as generally understood.

We may imagine (among others) the following types of structures :—

(1) Minute particles of $\gamma$ and $\beta$ perfectly evenly intermixed, their disposition being governed by the laws of probability only and not by any system of crystallization. This in a crystalline material, such as a metal, is of course extremely improbable. It would correspond to a very thorough mechanical intermixing of two finely-ground powders of the $\gamma$ and $\beta$ constituents.

(2) Minute particles of $\beta$ material embedded in a mass of $\gamma$ material, corresponding to $\beta$ nuclei forming and growing in the mass of $\gamma$ solid solution during the transformation of the material.

(3) The converse of (2), i.e. a network of $\beta$ material distributed throughout a ground mass of $\gamma$. In a material in which the structure takes the form of polygonal grains (the structure associated with $\gamma$ iron and most pure metals), this will correspond to a transformation of $\gamma$ to $\beta$ along the grain boundaries. The structure will therefore consist of a cellular network of $\beta$ constituent, the cells containing masses of $\gamma$.

It is not proposed to consider (1) in any detail. The occurrence of such a structure in any crystalline material is extremely unlikely. Moreover, it is hard to conceive of a structure of this nature which will not fall under that dealt with under (2). If the particles of $\beta$ and $\gamma$ are of irregular dimensions, or even if they are regular figures which are not packed together, there must of necessity be spaces between them which magnetically are equivalent to particles of $\gamma$ constituent, and the structure becomes equivalent to particles of $\beta$ embedded in $\gamma$, i.e. to that dealt with under (2). Considering then (2) and (3) only we arrive at the following conclusions.

*Structure type* (2) ; *$\beta$ grains in $\gamma$ matrix.*

(*a*) *Saturation density.*—This will clearly be proportional to the area of $\beta$ constituent lying in a section taken across the path of flux. Or if any line taken through the material cuts $p$ per cent of $\beta$ constituent, the saturation density will be $(p/100)B_s$, where $B_s$ is the saturation density of the $\beta$ constituent.*

(*b*) *Coercive force.*—Assuming that the flux passes in a straight line through the mass and does not follow a devious path from one $\beta$ particle to another, the coercive force will clearly be proportional to the percentage of $\beta$ constituent present in the mass, i.e. if $H_c$ be the coercive force of the $\beta$ constituent that of the composite will be $(p/100)H_c$.

(*c*) *Remanence.*—This will depend upon the remanence of the $\beta$ constituent, the percentage of this present and, in addition, the coercive force of the $\beta$ constituent.

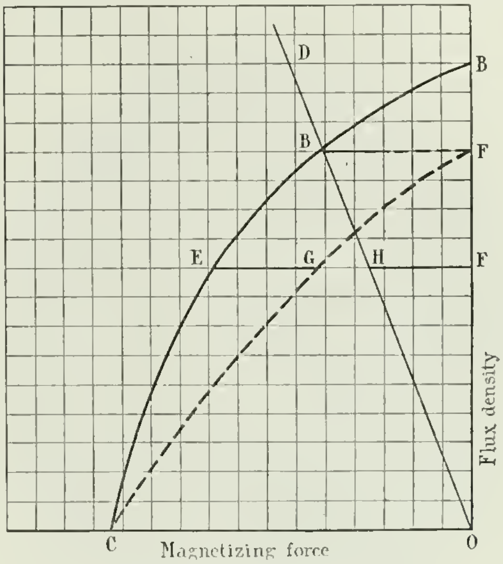


FIG. 10.—Construction for effect of added gap reluctance.

The $\gamma$ constituent will in effect introduce a reluctance into the magnetic circuit which will have the effect of moving the apparent remanence along the $BH$ loop towards the point $B = 0$, $H = -H_c$. The extent to which this point is moved will clearly depend not only on the reluctance in the circuit, i.e. the amount of $\gamma$ constituent present, but also upon the coercive force of the $\beta$ constituent.

The value of the apparent remanence is best found by the graphical construction shown in Fig. 10. In this case the line OD is drawn at an angle to OB such that tan BOD = $(100 - p)/p$. Then B, the point of intersection of OD with the $BH$ curve for the $\beta$ constituent, gives the apparent remanence of the composite material, and the apparent $BH$ curve for the material will be one which can be obtained by setting all the horizontal intercepts between OB and the original curve back to the axis OB, i.e. making EG (in Fig. 10) = HF.

---

* It might at first be thought that if any line cuts $p$ per cent of $\beta$ material the percentage of $\beta$ in a sectional plane would be $p^2/100$ and that in the whole volume $p^3/10\,000$. This is, however, incorrect, for we may consider the whole of a sectional plane to be built up of a number of elemental strips, each consisting of $p$ per cent of $\beta$ constituent. If the proportion of $\beta$ constituent is the same at all points and in all directions, each strip will contain $p$ per cent of $\beta$ and the section will also contain $p$ per cent. Or, expressed mathematically, each strip of width $dx$ and length $y$ contains $(p/100)y\,dx$ of $\beta$ constituent, and the whole area contains $\int(p/100)y\,dx$ ; or, since $p$ is constant, it contains $(p/100)\int y\,dx$, i.e. $p$ per cent of its total area. The same reasoning may be extended from the plane to the solid figure, which also contains $p$ per cent of $\beta$ constituent.

(*d* $(BH)_{max.}$—The value of this quantity will be reduced both on account of the reduction in $H_c$ and also owing to the reduction in the values of $B$ as described above. Consequently the reduction in $(BH)_{max.}$ will be greater than the reduction in either $B_{rem.}$ or $H_c$ considered separately.

*Structure type* (3) ; *$\gamma$ grain transformed to $\beta$ along grain boundaries.*

(*a*) *Saturation density.*—Here, as under (2), the saturation density will be proportional to the area of $\beta$ constituent lying in a section taken across the path of flux, and will, as before, be equal to $(p/100)B_s$.

(*b*) *Coercive force.*—In general the $\beta$ constituent which comprises the grain boundaries will form continuous chains extending throughout the material. There will hence be continuous magnetic circuits formed of ferric material. The coercive force in such a case will never be less than the true coercive force of the material and will in general be greater, as the length of path of the flux in the material will be greater than the shortest distance between two polar faces. In general, if $\theta$ be the mean inclination which the flux path along the grain boundaries makes with the shortest distance between the two polar faces, the apparent coercive force will be $H_c/\cos\theta$.

(*c*) *Remanence.*—This will be less than the remanence of the $\beta$ constituent for two reasons ; first, owing to the fact that a portion only of the cross-section of the material is carrying flux, and secondly, for the reason that the average direction of flux is not parallel to the axis of the material. Hence the density as usually calculated normally to the axis will be reduced in the proportion of 1 to cos $\theta$, and the remanence will therefore be equal to $(p\cos\theta/100)B_{rem.}$, where $B_{rem.}$ is the true remanence of the $\beta$ component.

(*d*) $(BH)_{max.}$—If the $\beta$ constituent forms closed chains which behave truly as a series of magnetic circuits in parallel, the $(BH)_{max.}$ figure of the whole mass will clearly be proportional to the amount of magnetic material, and will therefore be equal to $p/100$ times the $(BH)_{max.}$ figure of the $\beta$ constituent.

Summarizing the conclusions we have just reached we may say that :—

(1) The saturation density is determined only by the amount of $\beta$ constituent present, and is independent of the structure.

(2) The remanence is diminished to a much greater extent when the $\gamma$ constituent takes the form of envelopes surrounding masses of $\beta$ than when the $\gamma$ is itself surrounded by $\beta$.

(3) The coercive force may be increased by the presence of the $\gamma$ constituent when the $\beta$ forms the envelope of $\gamma$ grains, but is diminished when the converse is the case.

(4) The value of $(BH)_{max.}$ is proportional to the $\beta$ content when this forms the grain envelopes. In the converse case the $(BH)_{max.}$ diminishes more rapidly than the $\beta$ content does.

*Evidence in support of foregoing theory.*—The theory just put forward is to a large extent conjectural, and in order to establish, or disprove, its correctness, a large amount of work on a number of different steels, both plain carbon and alloy, will be necessary. Although much work has been done on the magnetic properties of steels, little has so far been attempted in the direction of a correlation of their magnetic properties and their microstructure. The class of steels which have been available to the author for testing the correctness, or otherwise, of his assumptions are limited in extent, and the work involved had to form part of a works routine and could not be treated as a matter of pure research. It is felt, therefore, that much more work is desirable, and that such work should be carried out under conditions which will better enable the different variables to be kept under careful control.

The steels which have been particularly examined belong to the cobalt-chromium group, containing from 10 to 35 per cent cobalt, with varying percentages of chromium and carbon, and in some cases other elements such as tungsten and molybdenum. The steels with the higher chromium percentages were air-hardening steels, while those with the lower percentages required hardening in oil. Practically all the evidence has been drawn from the air-hardening steels, as in this case the changes which take place in the steel are better under control, and take place so slowly that they can be accurately observed. The steels all possessed very similar characteristics. The temperature for hardening ranged from 950° C. to about 1 030° C. Heating to temperatures of 1 150° C. and upwards and cooling in air retained practically all the iron in the $\gamma$ state, giving a non-magnetic steel. On reheating this non-magnetic material a very pronounced recalescence occurred at from 700° C. to 750° C., accompanied by an expansion in volume, and a change to the magnetic condition, accompanied by a low coercive force. Cooling at the appropriate rate from the hardening temperature gave in every case a material of high coercive force, remanence, saturation density and $(BH)_{max.}$ In such a case the microstructure revealed a practically structureless grey mass, occasionally exhibiting the grey needle-shaped markings characteristic of martensite. In the case of high-chromium alloys small rounded masses, doubtless complex carbides, were frequently observed.

The author is of opinion that the following notes, dealing with one particular grade of steel, afford a considerable amount of evidence in connection with the theory put forward. The microstructure of the material, after heating to 1 150° C. and cooling in still air, is shown in Fig. 8. It consists of a number of polygonal grains of $\gamma$ iron remaining white after long exposure in nitric acid and practically all other reagents, the thin grain boundaries only showing dark. The size of the grains appears to depend upon both the maximum temperature and the length of time it is maintained, the grains tending to grow and the rate of growth being more rapid at the high temperatures. The material shows no signs of heat absorption or emission during cooling from the highest temperature reached, indicating the absence of any change of state. The material is almost completely non-magnetic. The remanence rarely exceeds 1 500, the saturation density (reached only in very high fields) is rarely more than 4 500 to 5 000, and the coercive force ranges from 100 to 150. On reheating the material practically no change, either in volume or magnetic properties, appears below 650° C. Between this point and 750° C. there is, however, a sudden and extremely well-marked point of heat emission, the temperature usually rising spontaneously to 800° C. or over. This is accompanied by an equally sudden expansion in volume and a recovery of magnetic properties, the remanence rising to 7 000 and upwards, the saturation density to 15 000 and upwards, while the coercive force usually falls to about 70 or 80. Fig. 11 shows graphically the changes which occur on reheating.

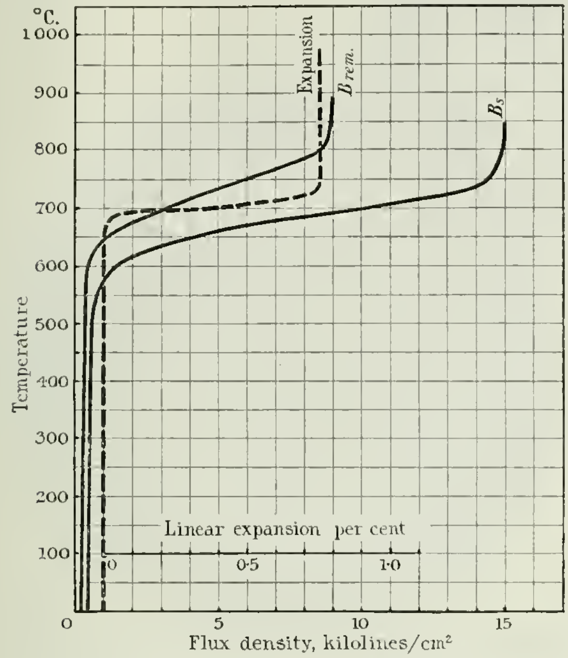


FIG. 11.—Volume and magnetic changes which occur on reheating a cobalt-chrome steel in the austenitic (γ) condition.

*Note.*—As these curves are plotted from observations at temperature-intervals of 50 deg. C., their general shape is correct.

The microstructure of the material after this change has occurred is shown in Fig. 12. It will be seen that a transformation has occurred along the grain boundaries, the white non-etching $\gamma$ iron becoming transformed into a material which etches very rapidly. The centres of the grains, however, appear to remain unchanged, but they tend to diminish in size if the duration of the heating be increased or if the material be given a series of successive heatings to 750° C. All the evidence available would seem to show that the dark grain boundaries are $\alpha$ iron, probably akin to sorbite and even in some cases to pearlite. In fact, in one or two cases it was possible to obtain evidence of the existence of a composite structure of a pearlitic character, although in general the grey boundaries were not capable of resolution.

The fact that portions only of the grains are transformed from $\gamma$ to $\alpha$ iron would appear to require some explanation. It might be accounted for by either of two suppositions :—

(1) A difference in chemical composition between the outside layers of the grains and their centres, or

(2) A retardation due to the change of state along the grain boundaries.

Of these alternatives the second is by far the more probable. In a true solid solution, such as the $\gamma$ constituent undoubtedly is, there is no reason to expect a separation into regions of varying chemical composition and, further, such a separation would hardly conform with the well-marked point at which change of state occurs on reheating.

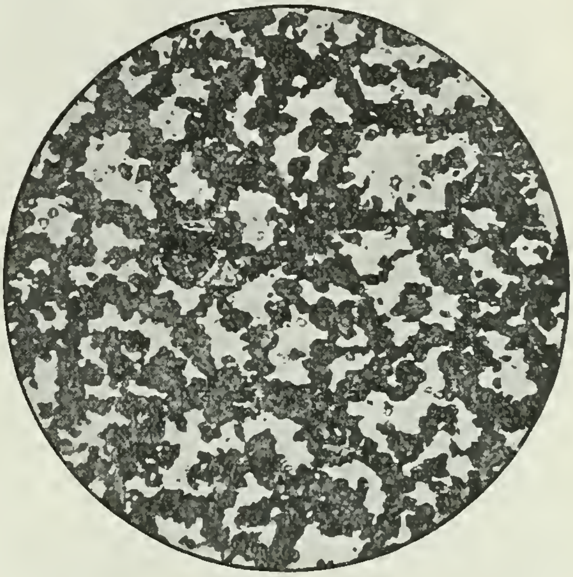


FIG. 12.—Cobalt steel heated to 1 150° C., cooled in air and heated again to 750° C.

White areas : untransformed austenite. Dark areas : eutectoid akin to sorbite and containing segregated carbides. Magnification : 150 diameters.

The second alternative is, on the other hand, entirely in agreement with the properties of the materials concerned. The very considerable expansion which accompanies the ($\gamma$–$\beta$) or ($\gamma$–$\alpha$) change would have the effect of setting up heavy internal pressure on the grain centres, and this pressure would undoubtedly have the effect of inhibiting the ($\gamma$–$\alpha$) change. Further evidence is, moreover, afforded by the fact that in the skin of the material the ($\gamma$–$\alpha$) change does not take the form of a transformation along the grain boundaries, but of actual changes in the grains themselves. Fig. 13 is a microphotograph of the material taken near the edge of the bar. It will be clearly seen that the change on the surface has occurred inside the crystalline grains, while inside the material, where the compressive stresses have full play and cannot be relieved by yielding of the metal, the change has occurred along the grain boundaries only.

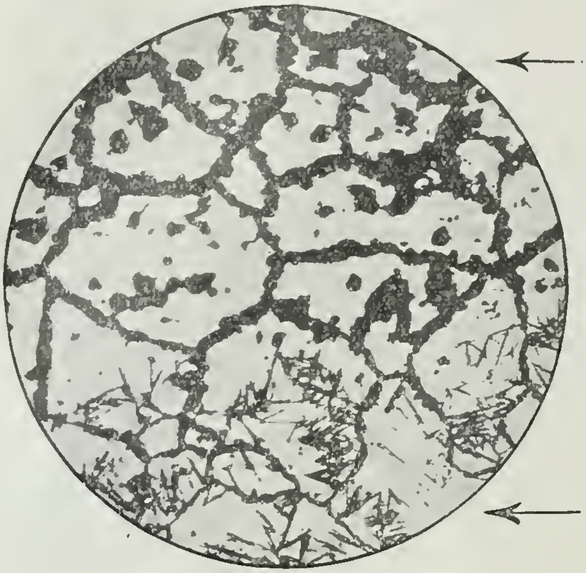


Fig. 13.—Cobalt steel heated to 1 150° C., cooled and reheated to 750° C. Microphotograph at edge of bar, showing alternative types of breakdown of austenite. Magnification: 150 diameters.

It can readily be imagined that cooling and reheating to 750° C. or so will be more effective in completely breaking down the $\gamma$ constituent than retaining the material at this temperature for a prolonged time. There is doubtless a condition of comparatively stable equilibrium between the bulky $\alpha$ material along the grain boundaries and the highly compressed $\gamma$ grain centres which makes any change of state very slow. Cooling and reheating the material will in all probability cause a redistribution of stress throughout the material, and this will permit the grain centres also to change state. Actual experience with the steel in question certainly shows that in cases where one reheating to 750° C. is insufficient properly to break up the $\gamma$ structure, cooling to atmospheric temperature, followed by a second heating, is successful in practically every case.

On heating the material in the $\alpha$ condition just described there is of course no point of recalescence such as accompanied the ($\gamma$–$\alpha$) change, and no change of state occurs below about 880° C. At this point, however, a well-marked heat absorption takes place, and, if the material be cooled from a temperature at which this heat absorption is complete, the steel is both mechanically and magnetically hard.

*Influence of cooling rate.*—The steel has the usual characteristics of an air-cooled alloy steel. That is to say, with very low rates of cooling recalescence occurs at about 750° C. and $\alpha$ iron is formed, the resulting material being both magnetically and mechanically soft. An increase in the rate of cooling suppresses the change at 750° C., but a fresh change-point occurs at a considerably lower temperature, the exact value of which depends upon the temperature from which cooling starts. The change occurring at this point is, however, not the ($\gamma$–$\alpha$) change, yielding a soft product, but the ($\gamma$–$\beta$) one, yielding a hard material.

*Range of ($\gamma$–$\beta$) transformation.*—The ($\gamma$–$\beta$) change as determined either thermally or magnetically does not occur at one definite point but is spread over a considerable range. Fig. 14, which illustrates the rate of growth of magnetic properties in a steel cooled from various temperatures, shows not only the effect of initial temperature upon the point at which the change commences, but also the range of temperature over which the change occurs. It will be noticed that with this particular steel the change is completed at atmospheric temperature, provided the initial temperature does not exceed about 1 050° C., but that for higher

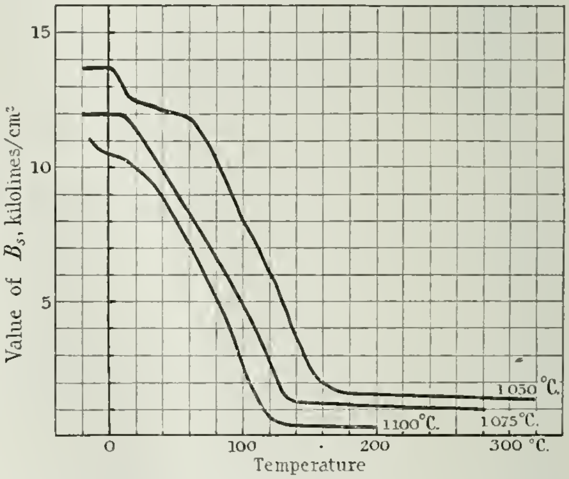


Fig. 14.—Growth of magnetic properties in cobalt steels cooled from various temperatures to room temperature (20° C.) and subsequently to 18° C.

initial temperatures than this, untransformed $\gamma$ constituent is clearly present in the hardened steel.

The width of range over which the change occurs is in all probability due to the reaction of the expanding $\beta$ constituent upon the untransformed $\gamma$ portion. The change is, in fact, of a very similar nature to that which occurs when the $\gamma$ material is reheated to 750° C., with the exception that the change is to the $\beta$ state instead of to the $\alpha$ state. It would appear that, to a large extent at all events, the $(\gamma-\beta)$ change occurs along the grain boundaries, and in so doing exerts a pressure on the grain centres, preventing further change. For any temperature there will, therefore, be a condition of equilibrium between the grain centre and the surrounding material, and it is not until the pressure which the expanding material can exert is unable to restrain the change that the grain centre becomes entirely transformed.

Since it is of importance that the $(\gamma-\beta)$ change shall be complete throughout the mass, we will briefly consider the factors which will assist its inhibition.

The effect of initial temperature has already been considered. It would appear that it is advisable to keep this as high as possible consistent with the $(\gamma-\beta)$ change being complete. Especially will this be the case in a high-carbon steel. The cooling rate must be sufficient to suppress completely the $(\gamma-\alpha)$ change at 750° C. Too rapid a cooling rate may conceivably suppress also a portion of the $(\gamma-\beta)$ change, and is therefore undesirable. In the steel in question, however, the factor which limits the cooling rate is the danger of the steel cracking. Too low a cooling rate, below 750° C., does not give rise to the $(\gamma-\alpha)$ change, but assists the expanding material along the grain boundaries in inhibiting the $(\gamma-\beta)$ change in the grain centres. A steel which has been cooled too slowly below 750° C. should, therefore, actually have a higher coercive force and lower remanence than one which has been cooled at a quicker rate, and this is actually borne out by experience with this particular steel. Much better and more uniform results are in fact obtained by quenching in oil or hot water at the point at which magnetism reappears, than by cooling outright in air.

Since the transition occurs in many cases at a temperature but little above that of the atmosphere, it is clear that the nature and temperature of the quenching medium will have an important bearing upon the result. In the case of oil quenching the latent heat of volatilization will be of no importance, as the transition point will be below the boiling point of the oil. The temperature and fluidity of the oil will therefore be the controlling factors. In the case of water-quenching the temperature of the bath may have an appreciable bearing upon the magnetic properties should it greatly exceed that of the atmosphere, while in the case of an air-cooled steel the amount and temperature of the cooling air will be of importance. The rate of cooling at a temperature of, say, 80° C. will vary quite considerably, depending on whether cooling takes place in cold outside air or in the neighbourhood of a hot furnace. If, therefore, the hardening temperature employed is such as to bring any part of the transformation into this region of temperature, the exact conditions of cooling must be carefully controlled.

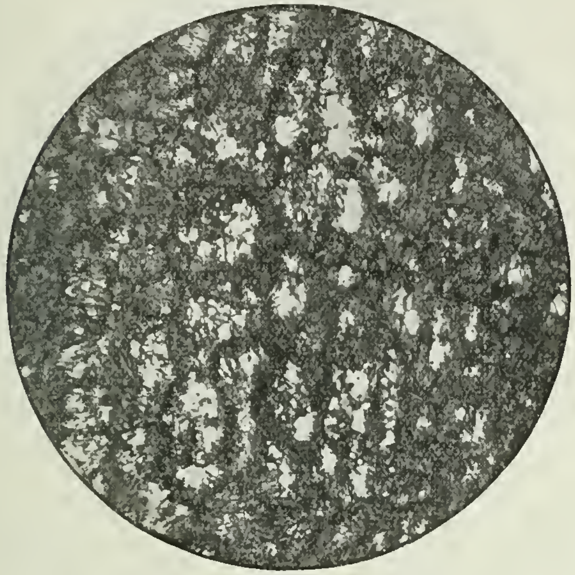


Fig. 15.—Badly hardened magnet, showing austenitic grain centres. Magnification: 150 diameters.

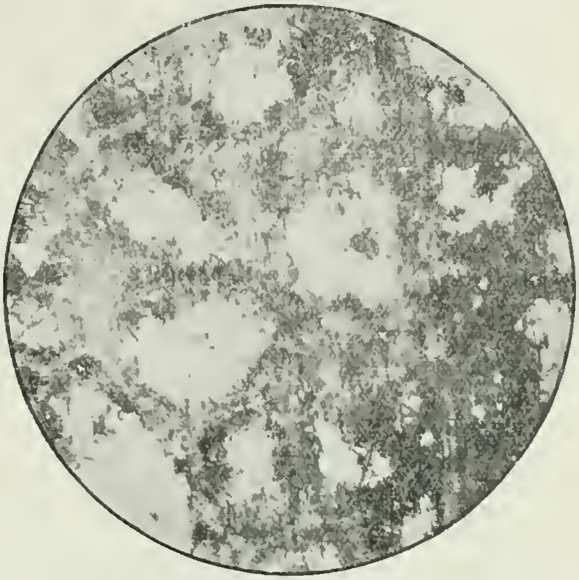


Fig. 16.—Badly hardened magnet. Retention of austenite, probably assisted by large grain size. Magnification: 150 diameters.

Figs. 15 and 16 are illustrative of the way in which partial transformation along the grain boundaries may occur. The increase in coercive force, due to the increased length of magnetic path in the case of incompletely transformed $\gamma$ constituent, is quite well marked.

It is further of interest to note that measurements taken on a magnet during the process of cooling from the $AR_2$ point indicate that the coercive force has a maximum value during the period, and that in the final stages of cooling at atmospheric temperature the coercive force is decreasing. This is completely in accordance with the supposition that the major portion of the $(\gamma-\beta)$ transformation occurs along the grain boundaries.

The size of grain undoubtedly has an important bearing upon the inhibition of the $(\gamma-\beta)$ change. Large grain size assists the bulky $\beta$ constituents in bringing intense pressure to bear upon the grain centres, and therefore promotes the retention of the $\gamma$ constituent. It is of importance, therefore, to limit the maximum temperatures to which the steel is subjected, also the length of exposure to such temperature, as both these factors tend to promote grain growth. On the other hand, in certain classes of steels, including the one considered, a preliminary heating to about 1 150° C. appears to be of great value as it increases the coercive force by about 25 per cent. The reason for this is not quite clear, but it would appear that this preliminary high-temperature treatment assists in getting the carbides into solution at the hardening temperature.

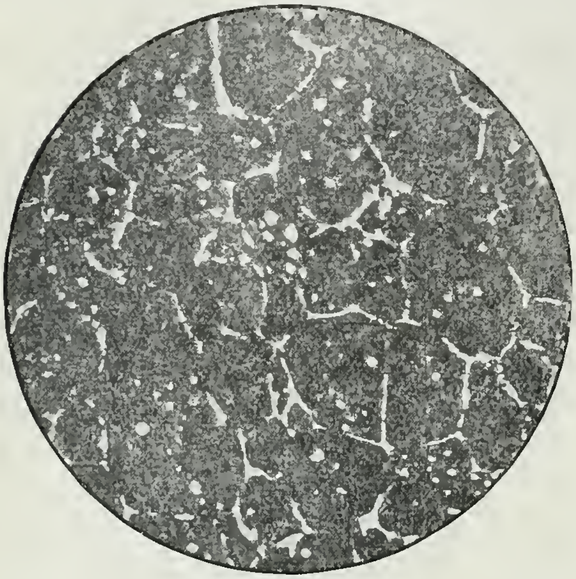


Fig. 17.—Non-magnetic grain boundaries, giving rise to low remanence. Magnification: 150 diameters.

The converse of Figs. 15 and 16, viz. the formation of a non-magnetic constituent along the grain boundaries causing more or less complete isolation of the magnetic $\beta$ grains, is fortunately only of rare occurrence, but is, as has already been pointed out, much more serious in its results. A steel in which this defect is present is generally characterized by both low remanence and coercive force. The microstructure of such a steel is shown in Fig. 17. The nature of the white constituent which has formed along the grain boundaries is not clear, but it is probably not identical with that forming the centres of the grains in Figs. 15 and 16.

The suggestion is put forward that it is excess of some constituent which is rejected along the grain boundaries during the hardening operation, and not, as in the case of Figs. 15 and 16, masses of untransformed austenite.*

*Effect of ageing.*—The $(\gamma-\beta)$ change in the hardened magnet would appear to follow a logarithmic law. At all events a slight increase of remanence and $B_s$ can be detected for several days after hardening. This is probably due to slight adjustments in the condition of equilibrium between the $\beta$ grain envelopes and the $\gamma$ centres. There is at the same time a slight tendency for $H_c$ to diminish, but this is more than offset by the increase in $B_{rem.}$, so that $(BH)_{max.}$ tends to increase and the magnet therefore improves in quality.

*Effect of supercooling.*—Since the effect of too high a hardening temperature is to depress the whole or a portion of the $(\gamma-\beta)$ change below atmospheric temperature, it would follow that a steel low in remanence on this account should be appreciably improved by further cooling. This is undoubtedly the case, and in several cases quite noticeable improvement has been effected by cooling the magnets either in a freezing mixture or in liquid air. The precise amount of the improvement which may be effected will clearly depend not only upon the extent of the supercooling, but upon the temperature from which hardening occurs, and in fact it should be possible to obtain a series of curves similar to those on Fig. 14 for various hardening temperatures and amounts of cooling. It would appear, however, to be somewhat open to doubt whether the same mechanism of hardening holds throughout the lower temperatures, and in particular whether for temperatures lower than atmospheric the $(\gamma-\beta)$ change takes the form of a growth inwards from the grain boundaries.

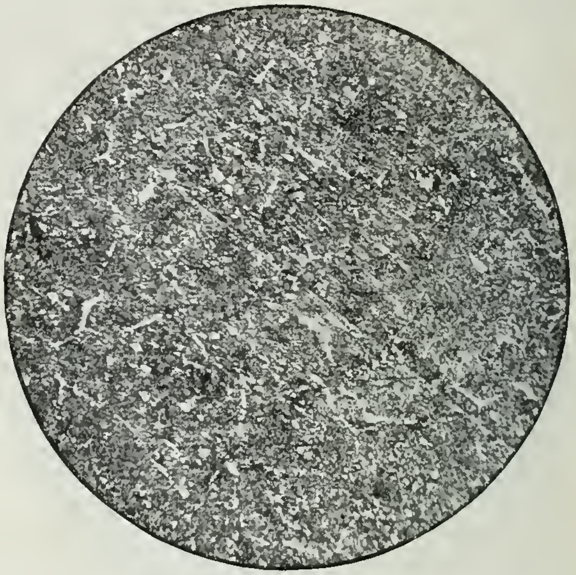


Fig. 18.—Commencement of formation of conditions shown in Fig. 17. The excess of carbides is segregating along the grain boundaries. Magnification: 150 diameters.

---

* This is confirmed by examination of steels in which the formation of the white grain boundaries is incomplete. The microphotograph of such a steel is shown in Fig. 18, which illustrates how the white patches (presumably carbides) tend to coalesce and arrange themselves along the grain boundaries.

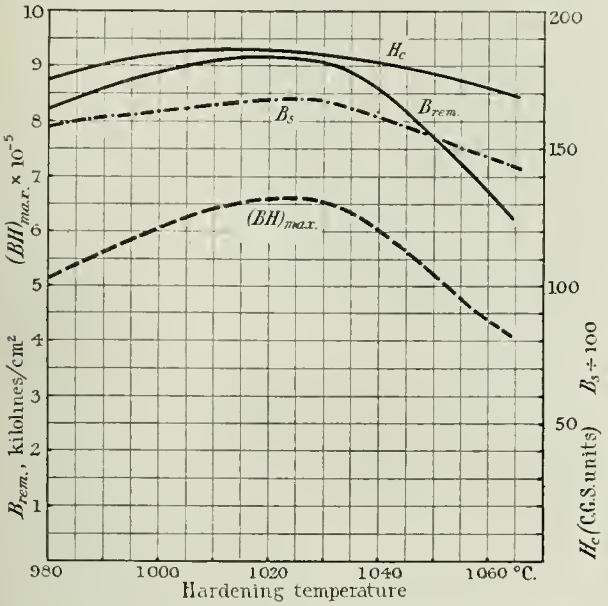


FIG. 19.—Effect of hardening temperature on properties of cobalt steel.

Experiments which were made upon a series of steels rendered almost completely non-magnetic by cooling from 1 150° C. and subsequently cooling to − 180° C. in liquid air showed that the ($\gamma$–$\beta$) change, although occurring under this treatment, was spread throughout the whole mass of the grains. The microstructure shows the whole grain mass to be broken up without any sign of thickened or transformed grain boundaries. Moreover, the coercive force, the remanence and the ratio of remanence to saturation value show conclusively that the transformed $\beta$ material did not form a continuous chain throughout the mass, but was surrounded by untransformed $\gamma$ matrix. It would appear, therefore, as if the mechanism of transformation at low temperatures were substantially different to that occurring at temperatures in the neighbourhood of 300° C., and it would further appear from some experiments made on the supercooling of a magnet only partially transformed at 20° C., as if a break in the cooling curve altered the mechanism of the change. In these experiments the growth of $B_{rem.}$ was observed from about 300° C. to 20° C. and was found to follow a smooth curve. After a period of several hours the magnet was further cooled to − 20° C. A slight gain in $B_{rem.}$ was noticed, but the gain was much less than would correspond to extrapolation of the original curve connecting $B_s$ and temperature. It would appear, therefore, as if the transformation of the grain borders once arrested could not be started again by further cooling, but that further transformation could only take place in the body of the grain itself.

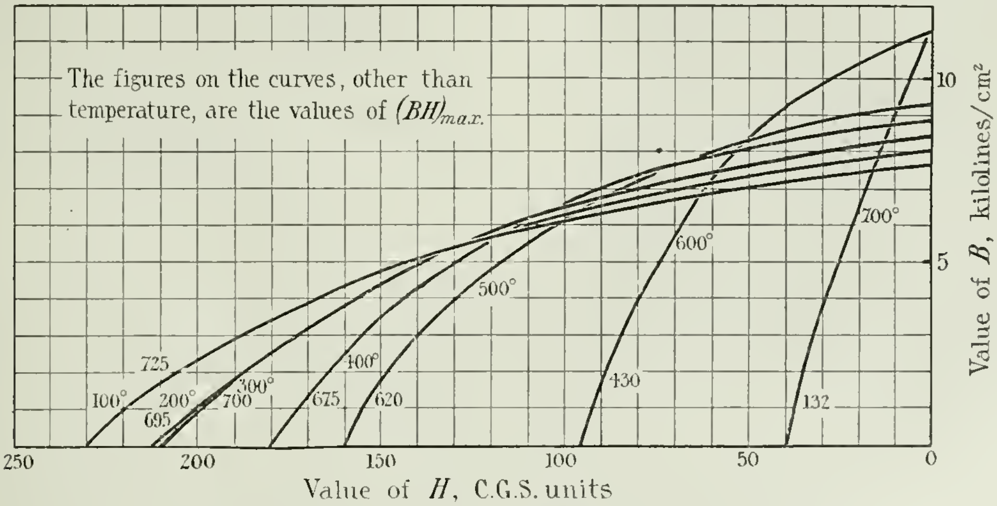


FIG. 20.—$BH$ curve for CK magnet after heating to various temperatures.

Before any definite pronouncement can be made more research work is required at temperatures below atmospheric, but it would appear to be fairly well established that although supercooling on a bad magnet is beneficial, the gain is not sufficiently great to make it a commercial proposition.

In illustration of the foregoing attention is drawn to Fig. 19, which expresses the relation between hardening temperature and magnetic properties for two typical steels. It will be seen that, as the hardening temperature is raised above that corresponding to the optimum value of $(BH)_{max.}$, the remanence and saturation value fall off first of all, followed later by the $(BH)_{max.}$ and coercive force. The remanence at first falls comparatively slowly, but later with much greater rapidity. The ratio of remanence to saturation density, at first nearly constant, diminishes rapidly at a later stage.

The correct interpretation of these results is probably that the first effect of too high a hardening temperature is to retain the grain centres in the $\gamma$ state, but that on the temperature being taken still higher, unchanged $\gamma$ material becomes interspersed between the magnetic grains. The structure, originally of Type (3), therefore changes with increased hardening temperature to Type (2).

*Steels containing both $\beta$ and $\alpha$ phases.*—Between the $\gamma$ and $\beta$ phases of a steel there is, as we have seen, a well-marked division accompanied by pronounced thermal and volume changes, and a sudden assumption of the magnetic condition. But between the hard or $\beta$ state and the soft $\alpha$ condition there is no such definite line of demarcation. The transition from one to the other is gradual, spread over a wide range of temperature, and is unaccompanied by any of the sharply defined thermal, volume and magnetic changes such as occur when the $\gamma$ constituent changes its state. It does not greatly matter for our purpose whether there is an actual allotropic change of state in the iron when the $\beta$ constituent is heated, or whether the changes are merely due to a gradual regrouping and crystallization of the carbide particles, leaving practically pure carbon-free $\alpha$ ferrite behind. The results, and their bearing upon the magnetic properties of the material, are in any case the same.

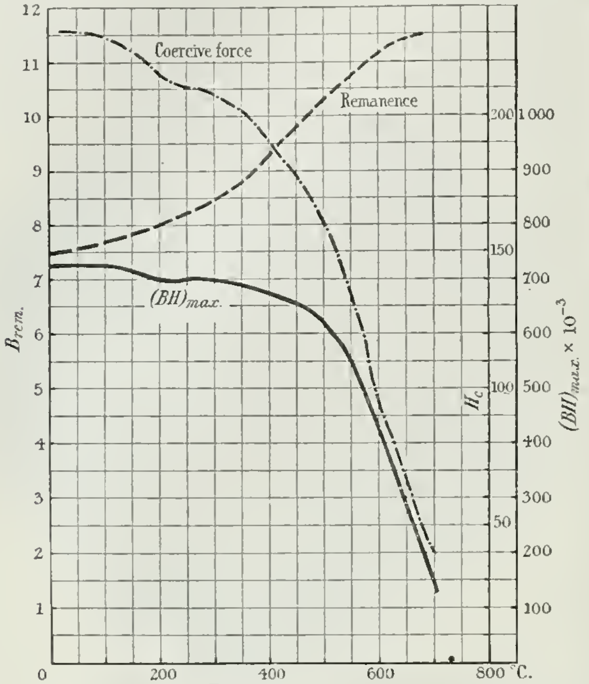


FIG. 21.—Effect of tempering on cobalt steel.

The effect of reheating or tempering a hardened magnet is in every case to produce an increase in remanence accompanied by a decrease in coercive force. This occurs to a slight extent with quite moderate amounts of heating. The extent of the "tempering" doubtless varies greatly with the class of steel, and will, for a given temperature, be much greater for a plain carbon steel than for a tungsten or chromium alloy.

For the steel which forms the basis of these notes the change in magnetic properties begins to be perceptible above about 150° C., and Fig. 20 gives the *BH* curve for a magnet of this material after successive heatings to a series of gradually increasing temperatures. Fig. 21 summarizes these results and shows how the important magnetic properties, $B_s$, $B_{rem.}$, $H_c$ and $(BH)_{max.}$ change with the successive degrees of tempering. It will be noticed that a steady gain in remanence is accompanied by a steady diminution in coercive force, with the result that the value of $(BH)_{max.}$, at first nearly constant, commences to fall off above about 300° C. and decreases very rapidly for temperatures of 500° C. and upwards. Further it will be noticed that the shape of the *BH* loop undergoes a marked change from the full loop of hyperbolic shape conforming to Lamont's law to a "lean" curve, almost a straight line, which cannot be so represented.

This lean curve is very similar in shape and general appearance to the curve which would be obtained if we considered two magnetic paths in parallel, of widely different coercive force. Let us suppose two magnetic paths in parallel with their terminal faces at the same potential. The resultant flux for any given M.M.F. between these terminal faces can be found by taking the algebraic sum of the fluxes in the two paths. This construction has been carried out in Fig. 22. It will be noticed that the point of inflexion where the curve for the material of low coercive force crosses the axis of *H* has introduced a corresponding depression in the combined curve very closely resembling the "lean" curve of Fig. 20. Of course we cannot expect a tempered magnet to behave in quite such a simple manner as two circuits in parallel, as the constituents comprising its structure may, as in the case just considered, arrange themselves in various ways, but the resemblance is sufficiently great to give a very strong support to the theory that the peculiar shape of the "lean" curves which do not obey Lamont's law is due to the presence

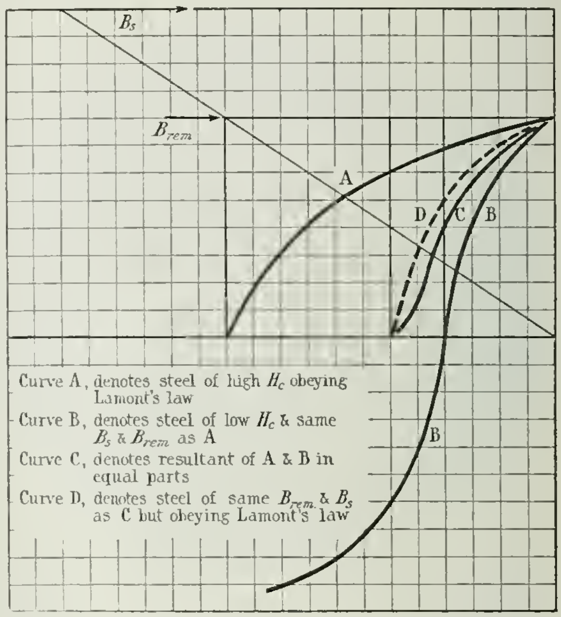


FIG. 22.—"Lean" loops produced by two phases of different coercive force in parallel.

of two constituents, both ferro-magnetic, but of widely different coercive force.

Attention is also drawn to Fig. 23, which gives the *BH* loop for a steel cooled too slowly through the critical range at 750° C. Fig. 24 gives the cooling curve of this magnet and shows clearly the heat evolution at 750° C. due to formation of the $\alpha$ phase. It also shows the further heat evolution due to the transformation of the remaining $\gamma$ material to the $\beta$ condition. Fig. 23 clearly shows that the properties of the resultant magnet are those of a mixture of $\beta$ and $\alpha$.

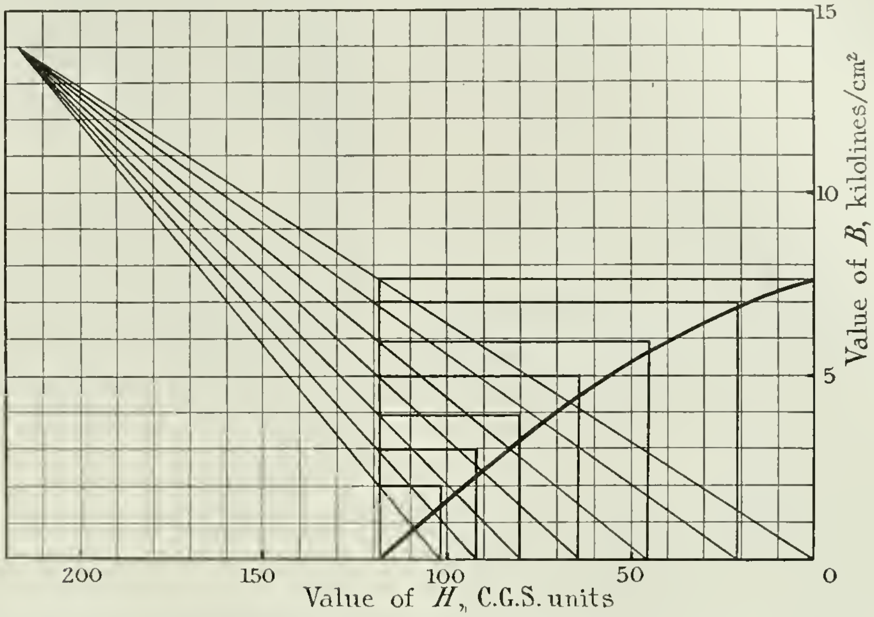


FIG. 23.—Cobalt magnet steel; cooling rate insufficient to suppress completely upper change-point. $\beta$ and $\alpha$ constituents both present, giving "lean" loop.

It is not proposed to deal in this paper with the question of why tempering should cause an increase of remanence. The reason for the decrease in coercive force is fairly obvious if we assume that the coercive force is due to the presence of dissolved carbides, for any tempering which gives rise to the separation of carbides as a separate constituent will of necessity diminish the amount in solution. It would appear to be fairly certain that tempering is not accompanied by any change in untransformed $\gamma$ iron which is present in the hardened magnet, as a number of experiments which have been made show that the $\gamma$ iron is untransformed below about 750° C. (see Fig. 11), so that apparently tempering is due to gradual transformation of the $\beta$ constituent. As tempering is found to reduce invariably the value of $(BH)_{max.}$, even if only slightly, it would appear that the most satisfactory magnetic materials are those in which the $\beta$ constituents form the whole of the material present.

If we concede that the aim in a permanent magnet is to produce the $\beta$ constituent to the exclusion of the $\alpha$, it will be advisable to consider under what conditions the $\alpha$ constituent may be formed during cooling or quenching. In the first place slow cooling through the upper critical point will permit the $(\gamma-\alpha)$ change to take place directly, and must be prevented. It is well to remember that at this point a very considerable heat evolution occurs, and that this heat evolution will tend to maintain the temperature at this point, and will thus tend to permit the whole of the $(\gamma-\beta)$ change to occur. As at this point the $\beta$ constituent transforms immediately to $\alpha$, the net result is that the $(\gamma-\alpha)$ change occurs and the magnet is soft. Very quick cooling through the upper critical point is there-

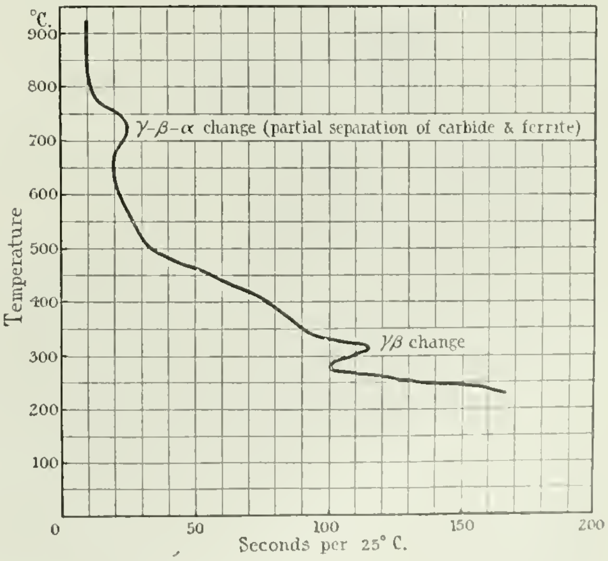


FIG. 24.—Cooling curve for magnet to which Fig. 23 refers.

fore essential, but below this point it would appear that the cooling rate is not of such great importance.

The ($\gamma$–$\beta$) change is, as we have seen, spread over a considerable range, and, since it is clearly necessary that it shall be complete at atmospheric temperature, it appears as if, at all events with the steel considered, this change must commence at a temperature not lower than about 200° C. It would therefore seem that certain portions of the material which assume the $\beta$ state at this temperature must pass successively through all temperatures between this and atmospheric, and, if the tempering of the $\beta$ constituent is a process that occurs equally on a rising or falling temperature, no further tempering of these portions should occur on heating the magnet up to the temperature at which they were formed. Conversely, if the $\beta$ constituent formed at a lower temperature and reheated to, say, 200° C. has a certain maximum value of $H_c$ and $(BH)_{max.}$, it would appear that the portions of the magnet of earlier formation cannot exceed these properties, although other portions formed subsequently might conceivably do so. It would seem also that in a magnet in which the ($\gamma$–$\beta$) change is spread over a considerable range, perfect homogeneity of constitution is not to be expected.

Although recent work on the hardening of steels seems to show that a constituent may be formed above and cooled without change through a temperature range at which its properties would be greatly modified by tempering if it were reheated to such range, yet experience with the class of steel described would seem to bear out this hypothesis in that the best magnets are obtained when the initial temperature and cooling rate are such that the $(\gamma - \beta)$ change is only just complete at atmospheric temperature. It is probably partly for this reason that alloy steels, such as tungsten or chromium steel, give much better magnets than plain carbon steels, but it is likely also that a further contributory cause lies in the relative immobility of the complex molecular groups which are formed by these alloys. Not only is the change-point of the steel lowered, but the rate at which regrouping into the transition products of troostite, sorbite and, finally, pearlite can occur is very materially reduced so that it is easier to retain the $\beta$ constituent at atmospheric temperature even with low rates of cooling.

There would appear to be the fundamental difference between the change we have described as the ($\gamma$–$\beta$) change and that which we have termed the ($\beta$–$\alpha$) in that, while further cooling below the point at which transformation begins increases the instability of the $\gamma$ constituent, it has no corresponding effect upon the $\beta$ phase, the transformation of which can only be brought about by heating above the temperature of its formation. As to whether the $\beta$ phase is truly stable or whether any very slow transformation is continually taking place it is difficult to state. Certainly in the case of tempering by heating above the formation temperature there is a distinct time interval which is necessary before a steady condition is attained, i.e. a hardened magnet heated to, say, 400° C. for one minute is not reduced in coercive force to such a great extent as if heated for one hour, so that any ($\beta$–$\alpha$) transformation occurring during quenching will depend greatly upon the cooling rate as well as upon the temperatures passed through.

## Conclusions.

(1) The properties of a properly hardened permanent magnet may be represented to a sufficient degree of accuracy for most practical work by the relation of Lamont's law, and the graphical construction derived therefrom may be used to predict the complete performance of the magnet when three points on the curve are known.

(2) The properties of an actual magnet depend upon—

(*a*) The constituents present.
(*b*) Their grouping and micrographical constitution.

With the same constituents arranged in different ways widely divergent results may be obtained.

(3) The constituent which should be aimed for is the first transformation product below the $\gamma$ or non-magnetic condition. This should form the whole mass of the magnet. In actual magnets it may occur associated with—

(*a*) Unchanged $\gamma$ material.
(*b*) Further stages in the transformation to the soft or $\alpha$ condition.

(4) In magnets in which a non-magnetic constituent is present, much less harm is produced by its presence when it forms the centres of cells of magnetic material than when it is interspersed between magnetic particles. In most magnets which have a granular structure any $\gamma$ constituent is usually present in the centre of the grains and acts chiefly as a diluent. It may sometimes cause a slight increase in coercive force. In cases where the non-magnetic constituent surrounds and separates the magnetic particles a very great reduction of remanence and $(BH)_{max.}$ occurs. In such a case the ratio of saturation to remanent density is very large. Such a condition appears to occur in steels which are made magnetic by subsequent supercooling, e.g. in liquid air. A steady cooling from the hardening temperature without any pauses which may arrest the process of transformation appears to be desirable.

(5) In order to comply with (3) above the ($\gamma$–$\beta$) transformation should take place at the lowest temperature consistent with the transformation being completed at atmospheric temperature. The cooling rate appropriate to this will depend upon the composition of the steel and the hardening temperature.

In order to ensure uniformity throughout the mass of the magnet the temperature gradient throughout it must be small so that the whole of the material cools at the same controlled rate. Hence the superiority of air- or oil-cooled steels, especially for large sections.

(6) The expansion of the material when changing from the $\gamma$ to the $\beta$ state has an important bearing upon the phenomena of hardening. It tends to broaden the region covered by the transformation and to assist the retention of non-magnetic centres in the grains. On this account a coarse-grain structure is liable to give poor magnetic results.

### Suggestions for Further Work.

It is felt that this paper is very incomplete. In many ways the theories put forward are conjectural. They are based generally upon a certain amount of practical experience in the workshop treatment of cobalt-steel magnets. To substantiate them and push them to a logical conclusion requires much careful laboratory work which the author is not in a position to carry out, and it is hoped that this paper may be of some value in suggesting possible lines of attack upon this admittedly complex subject. Quite possibly many of the theories will be shown to be wrong, but this will be of no matter should others be evolved which give us a better grasp of the mechanism of hardening and the production of a permanent magnet. In particular it is desirable that much more careful studies should be made of the magnetic changes in a cooling magnet, and that these should be taken over a large range of cooling temperatures extending in many cases well below atmospheric. Careful correlation also should be made of the magnetic, thermal and volume changes, and the microstructure should, of course, be examined wherever this can be done with profit.

Having established what may be termed the basic principles of hardening, studies should be made of the influence of the various alloying elements upon magnet steels, in every case investigating their effect upon the position and character of the various transformations, as well as upon the chemical compounds which they may form. Particular attention should be paid to the metal cobalt which, instead of being chiefly of importance in so far as it affects the transition points of iron as do the metals tungsten, molybdenum, chromium, etc., appears to be capable of forming with metallic iron an alloy $Fe_2Co$, which is possessed of quite remarkable magnetic properties, and which, in association with carbon, chromium, etc., will give very high coercive forces. This alloy, moreover, appears to form an uninterrupted series of solid solutions with metallic iron which make available a whole range of materials of widely varying magnetic properties, but all superior to the existing tungsten and chromium steels.

The harmful effects of impurities and the power of the usual ingredients such as manganese, silicon, sulphur, phosphorus, etc., to affect the structure of steel, has been already worked out as far as applies to tool steels and kindred materials, but a critical study showing exactly what effects these may have upon a permanent magnet is yet waiting to be carried out.

The problems involved are difficult, but should lead to important results. Already steels are available and in daily use which are four times as good as the old tungsten steel which held sway for so many years, and it can hardly be thought that finality has yet been reached.

In conclusion the author would express his indebtedness to the various steel firms whose materials have furnished the information which has been put forward. Among others he would mention the Cobalt Magnet Steel Co., Messrs. Steel (Sheffield), Ltd., and Messrs. Vickers, Ltd. He would particularly mention his indebtedness to Mr. J. F. Kayser of the Cobalt Magnet Steel Co. for very much information and assistance, for several of the microphotographs and for most valuable advice at all stages of the work. He is also indebted to the M-L Magneto Syndicate, Ltd., in whose works and laboratories all the information was obtained. He would also acknowledge the help and assistance of his assistants Messrs. Betteridge and Laird in the experimental work which, involving as it did the recording and plotting of some hundreds of *BH* curves, was often of an arduous nature.

## APPENDIX.

### The Method Employed for Testing Permanent Magnets.

The device employed for making the tests, the results of which are given in the paper, is not in any way novel, but the apparatus described has gone through a considerable process of evolution, as the result of which a testing gear has been developed which is direct reading over a large range of sections and lengths of magnets, and in which there is no necessity for the magnet to fit the magnetizing coils closely.

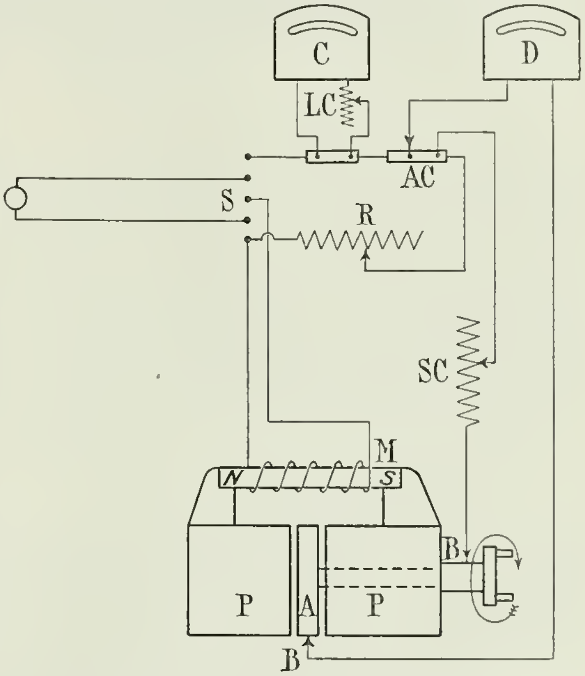


Fig. 25.—Diagram of connections for magnet-testing gear.

The actual measuring portion of the apparatus consists of a small iron disc revolved at a constant speed between a pair of pole faces, on which rests the magnet under test. A magnetizing coil is slipped over the magnet, and the current in the coil varied as desired for magnetizing and demagnetizing purposes.

The iron disc is mounted on a bronze spindle and has a bronze ring fixed on its outer edge, and brushes run on the spindle and on the ring, constituting a small unipolar generator. The voltage induced in the disc is therefore a measure of the flux provided by the magnet.

In order to make the instrument read the value of $B$, without the necessity for calculations, a variable resistance (SC in Fig. 25) is inserted between the revolving disc and a millivoltmeter, which measures the induced voltage. This resistance has a slider working on a graduated scale, and the resistance and graduations are so proportioned that when the slider is set to the calibration on the scale corresponding to the sectional area of the magnet, the millivoltmeter gives a reading indicative of the flux density in the magnet. In the same way compensation is made for various lengths of magnets by placing a variable resistance (LC in Fig. 25) between the shunt in the demagnetizing circuit and the ammeter which measures the current, and which gives, therefore, a reading of the value of $H$.

A further correction is necessary if the coils do not fit the magnets closely, as when the current is flowing in the coils there will be a flux in the air space surrounding the magnet, and this flux will be picked up by the measuring instrument and recorded as if it were flux in the magnet itself. To compensate for this a shunt, AC, is placed in the demagnetizing circuit. A sliding contact on this taps off a certain proportion of the voltage-drop and opposes it to the voltage induced in the revolving disc. The voltage-drop in this shunt is, of course, proportionate to the current, and so also is the voltage induced in the revolving disc by that portion of the flux which is contributed by the air space in the magnetizing coils. It is therefore possible to compensate exactly for this air flux and make the reading on the millivoltmeter indicate truly the density in the magnet itself. Further, if the shunt AC be so adjusted as to compensate not for the air space between the magnet and the surrounding coil, but for the whole of the air space enclosed by the coil, including that of the magnet itself, the reading obtained will be not the value of $B$ in the magnet as ordinarily given, but the value of $4\pi I$, or the true ferric density in the iron itself. The apparatus can therefore be very readily adapted for taking quick readings of the saturation density in the iron. For this purpose it is only necessary to move the reversing switch S (Fig. 25) into the magnetizing position and take the reading on the millivoltmeter D.

# REPORT ON RESEARCHES ON THE CHEMICAL AND PHYSICAL PROPERTIES OF INSULATING OILS.

(Report received from the British Electrical and Allied Industries Research Association.)

## Contents.

Page
Preface .. .. .. .. .. .. .. 661
**Part I.** General Review of Work .. .. .. 661
Previous Publications .. .. .. .. 661
Present Investigations .. .. .. .. 661
Methods of Testing .. .. .. .. 662
New Sources of Supply .. .. .. .. 662
Colour Tests .. .. .. .. .. 662
British Standard Specification .. .. .. 662
Work of Foreign Countries .. .. .. 662
Researches in Hand .. .. .. .. 662
**Part II.** Résumé of Experimental Work .. .. 662
Programme .. .. .. .. .. 662
Test No. 1a: Tendency to Sludge .. .. 662
General Remarks .. .. .. .. .. 662
Object of Research .. .. .. .. 663
Methods of Test .. .. .. .. .. 663
Results of Tests .. .. .. .. .. 663
Consideration of Results .. .. .. .. 663
Modifications to Apparatus .. .. .. 664
The Kissling Test .. .. .. .. 664
Test No. 1b: Tintometric Determination of Colour of Oils before and after Sludging .. 665

Test No. 2: Loss by Evaporation at 100° C.

Methods of Test .. .. .. .. .. 665
Results of Tests .. .. .. .. .. 665
Consideration of Results .. .. .. 665
Test No. 3: Flash Point (Closed Test) .. 665
Test No. 4: Viscosity at Different Temperatures .. .. .. .. .. .. .. 668

Test No. 5: Chemical Reactions

(*a*) Acidity and (*b*) Alkalinity .. .. .. 669
(*c*) Iodine Absorption Value (Hübl's process) .. 669
Results of Tests .. .. .. .. .. 669
Consideration of Results .. .. .. 669
Test No. 6a: Density .. .. .. .. 670

Test No. 6b: Coefficient of Volumetric Expansion

Method of Test .. .. .. .. .. 670
Results of Tests .. .. .. .. .. 670
Consideration of Results .. .. .. .. 670

Test No. 7: Cold Test (Solidification)

Methods of Test .. .. .. .. .. 671
Consideration of Results .. .. .. .. 671

Test No. 12: Specific Heat

Method of Test .. .. .. .. .. 671
Results of Tests .. .. .. .. .. 671
Consideration of Results .. .. .. .. 672
Specific Heat of Unit Volume .. .. .. 672

Contents—*continued.*

Latent Heat of Vaporization

Page
Features Investigated .. .. .. .. 672
Description of Apparatus .. .. .. 672
Method of Test .. .. .. .. .. 672
Results of Tests .. .. .. .. .. 673

Vapour Pressures

Method of Test .. .. .. .. .. 673
Results of Tests .. .. .. .. .. 674
Consideration of Results .. .. .. .. 674

The Action of Catalysers

Features and Materials Investigated .. .. 674
Method of Test .. .. .. .. .. 674
Results of Tests .. .. .. .. .. 674
Conclusions .. .. .. .. .. 674

## Preface.

The Research on Insulating Oils was initiated by the Institution of Electrical Engineers, continued by the Electrical Research Committee and transferred to this Association.

The subject has been growing in importance in view of the increasing size and greater demand put upon transformers and oil switches, and would appear never to have received the thorough investigation it deserved. The results of the research should be of considerable assistance to designers and users of transformers and oil switches.

## Part I.

### GENERAL REVIEW OF WORK.

*Previous publications.*—Previous preliminary work done has been published in the *I.E.E. Journal* (1915, vol. 53, p. 146, and 1916, vol. 54, p. 497), and an article on the "Selection of the Best Form of Spark Gap for Electric Strength Tests" has been published in the electrical Press (see *Electrician*, 3 December, 1921, and *Electrical Review*, 18 November, 1921).

The technical report Ref. E/T15 ("Comments on the Method proposed by the American Society for Testing Materials, for determining the Electric Strength of Transformer and Switch Oils") has been issued to members of the Association, and forwarded to the American Society for Testing Materials for its information.

*Present investigations.*—The present report embraces the most important details, abstracted from the reports on its files, of the investigations on the chemical and physical properties carried out by the Association, and the Association is indebted to, amongst others, Mr. A. R. Everest, Mr. A. P. M. Fleming, Mr. J. L. Langton, Dr. A. C. Michie, the National Physical Laboratory, Mr. W. B. Parker, Mr. L. G. Radcliffe and Dr. A. Russell, for the execution of the work.

*Methods of testing.*—In selecting methods of testing, two principal considerations have been kept in view:—

(i) The quantities measured should be, as far as possible, chemical or physical constants and not empirical quantities.
(ii) Where the quantities observed vary with the conditions of testing, the conditions should correspond as closely as possible to working conditions.

In dealing with such complex bodies as oils these conditions have been by no means easy to observe, and the value of the work done may be measured to a large extent by the success attained.

*New sources of supply.*—With a view to extending the sources of supply of insulating oils, and especially the utilization of possible sources in the British Isles, inquiries have been made into the possibilities of Coal Tar Distillation By-products and of Shale Oils as sources of insulating oils. It has been concluded that there are no immediate prospects of assistance in these directions, but the matter will not be lost sight of.

*Colour tests.*—Change of colour on heating has been employed on the Continent as an indication of sludging characteristics, but after thorough investigation it is concluded that this method of testing could not be employed as a substitute for methods recommended, and that colour cannot be taken *per se* as giving any indication of the sludging characteristics of an oil.

*British Standard Specification.*—Based on the information supplied by the Association, after extensive inquiries and experimental investigations, a British Standard Specification for Insulating Oils for use in Transformers, Oil Switches and Circuit Breakers (No. 148—1923) has been issued by the British Engineering Standards Association.

The Specification will be revised and added to from time to time as the results of further investigations, which this Association is carrying out, come to hand. A full description of the apparatus and methods to be used in the proposed tests will be found therein.

*Work of foreign countries.*—The Association has kept in touch with work done in other countries, and it is felt that while the Specifications are rather more elaborate than others now in use, this represents a definite advance and will lead to improvements in the material obtained and in knowledge.

*Researches in hand.*—Experimental investigations are in hand on:—

(*a*) Thermal conductivity and transference.
(*b*) The effect of arcing on the physical and chemical properties of oils.
(*c*) Resistivity and its correlation with moisture content and electric strength, with special reference to the effect of contaminating particles on the electric strength in the light of new facts and data.

In this connection, investigations will be made on the centrifugal separator as a means of purifying oils.

In addition to the above, further work is in hand for the improvement of standards, and especially for further development of sludge testing, with a view to improvement and simplification of method.

## Part II.

### RÉSUMÉ OF EXPERIMENTAL WORK.

*Programme.*—The programme of the Insulating Oil Research Committee, as initiated by the Institution of Electrical Engineers, embraced the following:—

| Test No. | Nature of Test |
|---|---|
| 1*a* | Tendency to Sludge. |
| 1*b* | Change of Colour due to Sludging. |
| 2 | Loss by Evaporation at 100° C. |
| 3 | Flash Point "Closed." |
| 4 | Viscosity at Different Temperatures. |
| 5 | Chemical Reactions. |
| | (*a*) Acidity. |
| | (*b*) Alkalinity. |
| | (*c*) Hübl's Iodine Absorption Value. |
| 6*a* | Density. |
| 6*b* | Coefficient of Expansion. |
| 7 | Cold Test (Solidification). |
| 8* | Moisture Absorption. |
| 9* | Electric Strength. |
| 10* | Specific Resistance. |
| 11* | Thermal Transference. |
| 12 | Specific Heat. |

In addition to the investigations on the above tests, a résumé of the following three investigations is included in this report:—

(*a*) Latent Heat.
(*b*) Vapour Pressures.
(*c*) The Action of Catalysers.

### TEST NO. 1A: TENDENCY TO SLUDGE.

*General remarks.*—It may be said that the main cause of trouble from oil in transformers can be traced to the presence of air, which under the action of heat and accelerated by contact with certain metals oxidizes and polymerizes the oil, with the result that solid deposits are formed which settle on the windings and result in overheating. At the same time water and organic acids may form, which reduce the electric strength of the oil and may attack the materials of the transformer and casing. The best method of preventing these troubles is undoubtedly to exclude air from coming into contact with the oil. This is a matter of transformer design and in many cases could be readily accomplished.

As an instance of the effect of air, it may be mentioned that during a period of seven years one of the investigators heated a sample of transformer oil to a temperature of 150° C. for over 14 000 hours, air being excluded. There was no perceptible alteration in the oil, no formation of acids, no water and no deposits.

It is not maintained that all transformer oils would give as good a result as this, even if air were excluded, as many of the poorly refined oils have a certain proportion of oxygen in their composition. It is probably not possible to exclude air from all transformers and it was therefore necessary to standardize a test which would give not only an indication of the tendency of the various oils to deposit solid matter, but also a measure of their liability to form water and organic acids.

---

* See "Researches in hand" in previous column.

*Object of research.*—The sludging test is the most important test of the series.

The prime object of the research on sludging was to ascertain by a series of tests carried out by different laboratories upon one and the same set of oils and using a selected method of test, whether a sludging test was suitable for standardization for purchasing specifications of insulating oils. This includes the question of rapidity, ease of performance, concordance of results between duplicate tests and between different experimenters; also the degree of accuracy to which the determination can be performed and the discovery of any possible improvements in the method itself.

*Methods of test.*—Dr. Michie's original test employed air at 150° C., but it was decided to make investigations over a range of temperatures from 60° C. to 120° C. in order to find the temperature at which sludge in measurable quantities first forms.

Tests were also carried out with oxygen, which, it was anticipated, would somewhat increase the severity of the test, but whether it made other more drastic changes in the character of the test and the products produced was then uncertain though considered probable.

*Results of tests.*—The oils submitted represented three sources, viz.

East Asiatic (Burmah).
West Asiatic (Russian).
North American (U.S.A.).

The results indicated that the pale Russian oils were the best, but some American modern refineries have produced an American oil of equal merit under this form of test.

Table 1 gives the percentages of sludge formed by the different oils, using oxygen, between the temperatures of 60° C. and 120° C. Table 2 shows the amount of deposit formed with air between the temperatures of 100° C. and 150° C. The figures given in these tables were finally adopted after carefully considering all discrepancies due to variations in the conditions of the test, including the personal equation.

In all cases, both with oxygen and with air, the oil darkened in colour, the darkening increasing as the temperature was raised. The deposits which separated out were also darker in colour with the higher temperature.

*Consideration of results.*—The following conclusions were formed :—

(*a*) *Rapidity.*—Upwards of six tests can be performed simultaneously in apparatus in which arrangements are made to pass the oxygen (or air) through the flasks in parallel.

(*b*) *Ease of manipulation.*—The test *per se* is not difficult, and the reaction flask shown in Fig. 1 renders the manipulation of the sludge easier than was the case with the original flask used.

(*c*) *Concordance of duplicate tests.*—Duplicate tests obtained by individual workers appear to agree fairly satisfactorily.

TABLE 1.

*Percentage Sludge formed, using Oxygen at Temperatures from 60° C. to 120° C.*

| Oil No. | Percentage sludge at | | | | |
|---|---|---|---|---|---|
| | 60° C. to 80° C. | 90° C. | 100° C. | 110° C. | 120° C. |
| 1 (Burmah) .. | nil | 0·01 | 0·07 | 0·27 | 0·82 |
| 2 (Burmah) .. | nil | nil | 0·02 | 0·07 | 0·43 |
| 3 (Russian) .. | nil | nil | nil | nil | 0·11 |
| 4 (Same as No. 3; partly used) | nil | nil | nil | 0·16 | 2·6 |
| 5 (Partly used) | nil | nil | 0·04 | 0·13 | 0·37 |
| 6 (Russian) .. | nil | nil | nil | 0·03 | 0·41 |
| 7 (American) .. | nil | nil | nil | 1·1 | 2·5 |
| 8 (American) .. | nil | nil | 0·01 | 0·12 | 0·03 |
| 9 (American) .. | nil | nil | nil | nil | 0·46 |
| 10 (American) .. | nil | nil | 0·015 | 0·04 | 0·42 |

TABLE 2.

*Percentage Sludge formed, using Air at Temperatures from 100° C. to 150° C.*

| Oil No. | Percentage sludge at | | | |
|---|---|---|---|---|
| | 100° C. | 110° C. | 120° C. | 150° C. |
| 1 (Burmah) .. .. | 0·04 | 0·15 | 0·7 | 3·2 |
| 2 (Burmah) .. .. | trace | 0·04 | 0·2 | 2·8 |
| 3 (Russian) .. .. | — | — | — | trace |
| 4 (Same as No. 3; partly used) .. .. | — | — | — | 0·06 |
| 5 (Partly used) .. | — | 0·02 | 0·1 | 0·6 |
| 6 (Russian) .. .. | — | — | 0·06 | 0·35 |
| 7 (American) .. .. | — | — | — | trace |
| 8 (American) .. .. | — | — | 0·03 | 1·4 |
| 9 (American) .. .. | — | — | — | 0·5 |
| 10 (American) .. .. | — | 0·01 | 0·08 | 1·1 |

(*d*) *Concordance of results by different experimenters.*—The agreement between different experimenters was not good if all the reported results are considered, and all are given equal weight from the point of view of intrinsic worth. Owing to the following causes, it was not possible to attach equal weight to all the results obtained :—

(i) Some experimenters used distinctly different methods of weighing up the precipitates of sludge obtained.
(ii) One experimenter reported results only for the maximum temperature (120° C.).
(iii) In the case of Sample 4—a partly used Russian oil—the differences suggested imperfect sampling. This is a probable explanation, because this oil was "partly used" and probably contained sludge which, owing to its tendency partly to settle and partly to remain in solution, would not be evenly distributed in the samples as issued to the individual experimenters.

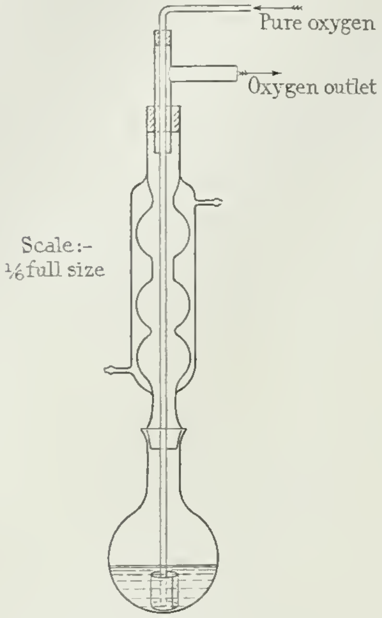


Fig. 1.—Modified sludging apparatus.

(iv) In most cases no meter was used for measuring the quantity of gas passed.
(v) In the case of the American oils Nos. 7, 8, 9 and 10, using oxygen, the precipitate of sludge was difficult to manipulate owing to its physical condition. These sludges were sticky colloidal varnish-like substances, very difficult to wash and dissolve. This characteristic is undoubtedly connected with the use of oxygen, since the same oils gave granular precipitates with air.

These difficulties have been fully considered in drafting the specification, and also in the selection of the figures appearing in Tables 1 and 2.

(*e*) *Air or oxygen.*—In every case where air was used the deposits were in the form of powders, while with oxygen sticky varnish-like substances were usually obtained.

The Association did not favour the use of oxygen instead of air (as originally suggested by Dr. Michie) for the following reasons :—

(i) Air and not pure oxygen comes in contact with the oil under actual working conditions.
(ii) The action of air is not the same as that of oxygen.
(iii) The results of the air sludge test correspond better than those of the oxygen sludge test with the liability of insulating oils in actual practice to form solid deposits.
(iv) The iodine values correspond better with the air values than with the oxygen values. The curves in Fig. 2 show the relation between the iodine values and the sludge values with air and oxygen.
(v) Taking all the results into consideration, it appeared that when using oxygen the accuracy as between different experimenters was not sufficiently good.

For the above reasons it was recommended that air be used in the standard method for specification purposes, that is, reverting to the original form of the test devised by Dr. Michie.

*Modifications to apparatus.*—The following modifications to apparatus were adopted :—

(*a*) *Reaction flask.*—The form used by some of the experimenters, consisting of a detachable bulb portion (flask proper) fitting into an all-glass condenser tube by means of a carefully ground-in joint (Fig. 1) is recommended, with the proviso that the ground-in joint should be situated above the surface of the oil in the hot oil-bath in order to ensure that there is no leakage of the oil from the bath into the apparatus.

(*b*) *Oil bath.*—The electrically heated forms appear satisfactory, but to make certain of uniform heating mechanical stirring should be used in all cases. Control of the temperature must be thermostatic.

(*c*) *Flow and regulation of gas through reaction flasks.*—This is undoubtedly the most important feature of the test.

(i) It is very important that the flasks be joined up to the gas (oxygen or air) supply on the parallel-flow principle, and not in series.
(ii) The gas flow must be measured by an accurate meter or some form of volumetric measurer which can be attached in rotation to the flasks. This matter requires much more attention than was given to it in the original investigation.
(iii) It is essential that the quantity of gas should be very uniform for every test made, and it should be delivered at a steady rate of flow. At present this feature seems the weakest point in the method. The use of air presents less difficulty than does the use of oxygen.

*The Kissling test.*—This test is used to a large extent on the Continent, and especially in Germany. It is a measure of the tar content of some of the acid compounds formed by the oxygen used, others being driven off at the high temperature. The material obtained by this test is small and would not precipitate in a transformer. The test does not take into account the catalytic action of copper.

It is considered that there is no connection between the tar value as given by the Kissling test and the sludge formed in a transformer. Some of the best oils give high Kissling values but practically no sludge.

### Test No. 1b: Tintometric Determination of Colour of Oils before and after Sludging.

The Lovibond apparatus used in this investigation was originally designed for testing petroleum oils, chiefly of the lamp-oil class.

The investigation showed that there did not appear to be any direct indication of commencement of sludging by colour-change, and the colour-change appeared to be gradual.

Colour/temperature curves for a definite stratum thickness indicated that the colour number increases slowly at first, but as the temperature is raised the increase becomes more rapid. For the better oils the change takes place at 90° C., while for those which deposit sludge the change appears to be at 60° C. to 70° C. This appears to be the clearest indication of sludging tendency given by the curves.

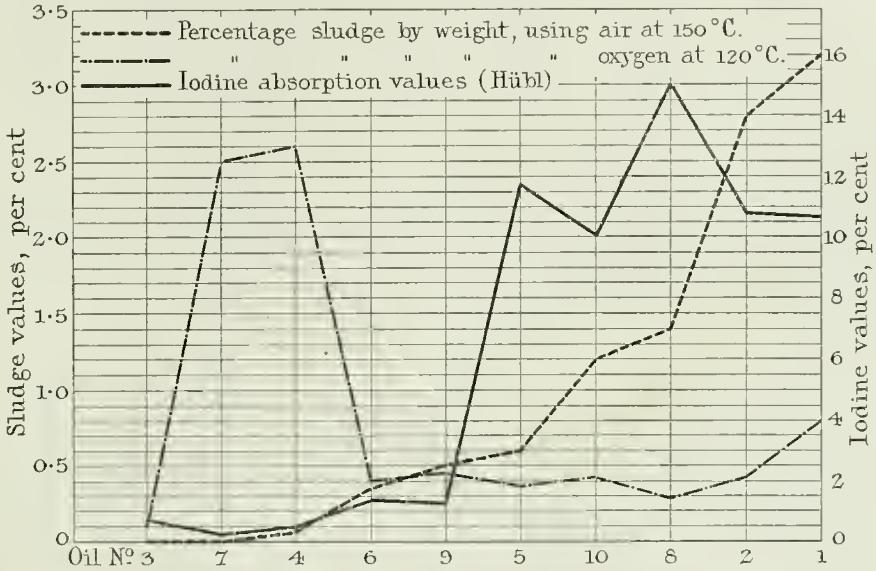


Fig. 2.—Relation between iodine and sludge values.

The presence of sludge in the oil does not appear to exercise any appreciable influence on the colour number.

The tests proved that this method is greatly influenced by the personal equation. After considerable experimental work it was concluded that colour tests could not be relied upon as criteria of the sludging characteristics of an oil, and could not therefore be substituted for other methods of examination.

### Test No. 2: Loss by Evaporation at 100° C.

*Methods of test.*—Three methods were suggested for comparison, one devised by Dr. Michie, another utilized by the B.T.H. Company, and the third was Archbutt's method. Only one set of values for the B.T.H. method is available and this was furnished by the B.T.H. Co.

The chief reason for including the Archbutt vaporimeter method was that it had been in use for lubricating-oil testing for many years, but it was found that the apparatus had not been definitely standardized and was open to considerable improvement in such matters as method of heating and control of temperature.

*Results of tests.*—Table 3 gives the results obtained with the three methods by different investigators.

*Consideration of results.*—The quantity of oil used and the shape of the container have a great influence on the rate of evaporation.

As regards the degree of accuracy required, speed of test, and general usefulness, both the first two methods appear satisfactory.

With regard to the significance of the evaporation results, it was evident that these afford a measure of the economy of the oil in use for transformers and switches, also of the safety of the oil, i.e. they show whether dangerous quantities of vapour are evolved which (having a flash point of 130° C. to 185° C.) could produce large-scale explosions if mixed with air and ignited.

It should be particularly noted that the evaporation does not afford any indication of the dryness of the oil, and cannot be made to do so with any really satisfactory result.

### Test No. 3: Flash Point (Closed Test).

The whole of the results reported are summarized in Table 4. It is only by extremely careful and systematic attention to details (many of which have not yet been standardized) that concordant work is attainable.

All the precautions mentioned in Sir Boverton Redwood's book " A Treatise on Petroleums " must be

TABLE 3.

*Test No. 2; Loss by Evaporation at 100° C. Percentage by Weight. Comparison of Results obtained by Standard B.T.H., Standard Michie, and Standard Archbutt Methods of Determining Loss by Weight at 100° C.; also Modifications of Archbutt's Method to ascertain its Relation to the other Methods.*

| Oil No. | B.T.H. Method. Standard 2 g; 8 hours | Dr. Michie's method; toluene vapour-bath. Standard 5 cm³ (about 5 g); 8 hours. Mean results reported by | | | Archbutt's vaporimeter method. Standard, 0·5 g; 1 hour. Means of tests reported by | | | | Modified Archbutt's method; mean of dup. B.T.H. results, using 2 g for 8 hours at 212° F.‖ |
|---|---|---|---|---|---|---|---|---|---|
| | | Investigator A * | Investigator B † | Investigator C ‡ | Investigator C; air at ? ° F.§ | Investigator B; air at 212° F.‖ | Investigator A; air at 172° F. | Investigator A; air at 212° F.‖ | |
| 1 | 1·94 | 1·2 | 1·43 | 1·31 | 0·70 | 1·03 | 0·32 | 1·4 | 1·25 |
| 2 | 1·82 | 0·9 | 1·46 | 0·835 | 0·53 | 0·38 | 0·26 | 1·0 | 0·88 |
| 3 | 1·08 | 0·9 | 1·09 | 0·615 | 0·74 | 0·64 | 0·28 | 0·84 | 0·77 |
| 4 | 2·60 | 1·7 | 2·27 | 1·46 | 0·82 | 0·88 | 0·45 | 1·6 | 1·53 |
| 5 | 0·33 | 0·4 | 0·35 | 0·29 | 0·20 | 0·35 | 0·10 | 0·3 | 0·275 |
| 6 | 2·98 | 2·5 | 2·73 | 1·42 | 1·10 | 0·93 | 0·67 | 2·35 | 2·04 |
| 7 | 0·53 | 0·5 | 0·50 | 0·225 | 0·31 | 0·50 | 0·22 | 0·5 | 0·31 |
| 8 | 3·21 | 2·3 | 2·61 | 1·425 | 1·25 | 0·77 | 0·68 | 2·1 | 1·625 |
| 9 | 1·70 | 1·4 | 1·89 | 1·29 | 0·54 | 0·53 | 0·52 | 1·6 | 1·16 |
| 10 | 22·66 | 15·5 | 15·11 | 11·05 | 7·70 | 8·27 | 3·0 | 13·1 | 11·27 |

* Investigator A used 5 cm³ volume for this test.

† Investigator B used 5 g for this test (equals 5·44 to 6·04 cm³ volume, according to the specific gravity of the oils).

‡ It is not clear from the report issued whether investigator C used 5 g or not: he states that "a standard weight" of oil was used, but gives no weighings.

§ There is some uncertainty regarding the real temperatures of the air passed over the oil in this experiment, no record of the same being given in the report issued.

‖ Temperatures determined by actual experiments. In the case of investigator B's tests, a new double-tube vaporimeter was used, whereas in investigator A's and investigator C's reports an old single-tube apparatus was used.

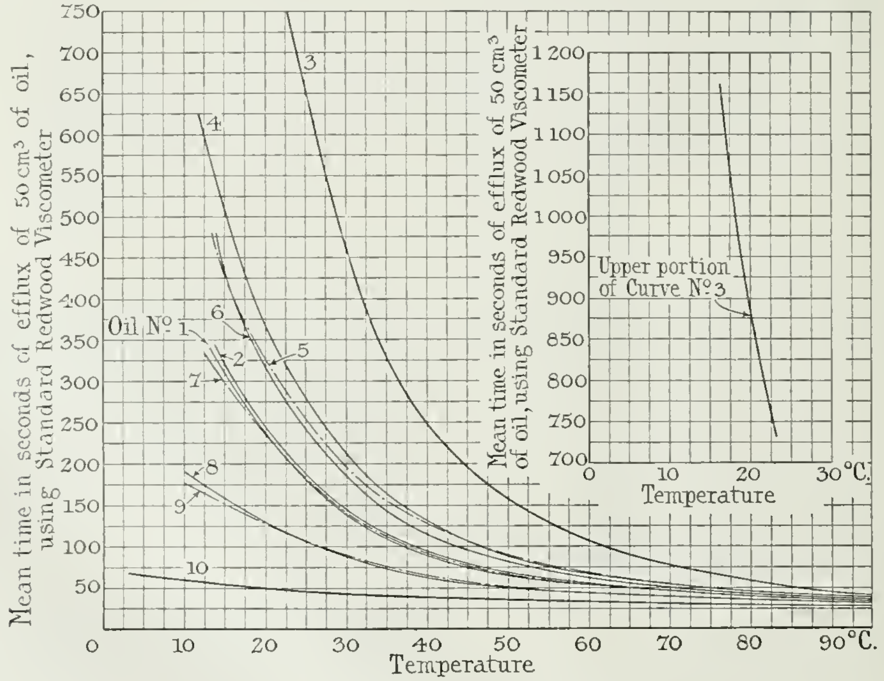


FIG. 3.—Test No. 4: Average viscosity at different temperatures for oils in Table 5.

TABLE 4.—*Test No.* 3 ; *Flash Point* (*Closed*). *Results Collected for Comparison.*

| Oil No. | Investigator | Instrument used | Results obtained | | |
|---|---|---|---|---|---|
| | | | Minimum | Maximum | Remarks |
| | | | °C. | °C. | |
| 1 | D | Gray | 175 | — | Average (*a*) 174·8 |
| | A | Pensky, M. | 176 | 177 | Average (*b*) 174·8 |
| | C | Gray | 179·4 | — | Maximum 179 |
| | E | Pensky, M. | 177 | — | Minimum 169 |
| | B | Gray | 169 | 170 | — |
| | F | — | not tested | not tested | Difference 10 |
| 2 | D | Gray | 176 | — | Average (*a*) 176·7 |
| | A | Pensky, M. | 178 | 179 | Average (*b*) 176·7 |
| | C | Gray | 179·4 | — | Maximum 179·4 |
| | E | Pensky, M. | 176 | — | Minimum 174·4 |
| | B | Gray | 174·4 | 174·4 | — |
| | F | — | not tested | not tested | Difference 5·0 |
| 3 | D | Gray | 184 | — | Average (*a*) 184·9 |
| | A | Pensky, M. | 181 | 183 | Average (*b*) 184·6 |
| | C | Gray | 187·7 | — | Maximum 188 |
| | E | Pensky, M. | 188 | — | Minimum 181 |
| | B | Gray | 182 | — | — |
| | F | — | 186 | — | Difference 7 |
| 4 | D | Gray | 177 | — | Average (*a*) 175·1 |
| | A | Pensky, M. | 175 | — | Average (*b*) 175·0 |
| | C | Gray | 180 | — | Maximum 180 |
| | E | Pensky, M. | 173 | — | Minimum 171 |
| | B | Gray | 171 | — | — |
| | F | — | 175 | — | Difference 9 |
| 5 | D | Gray | 174* | — | Average (*a*) 192·3 |
| | A | Pensky, M. | 197 | 198 | Average (*b*) 195·3 |
| | C | Gray | 197 | — | Maximum 198 |
| | E | Pensky, M. | 198 | — | Minimum 174 |
| | B | Gray | 190 | 191 | — |
| | F | — | 196 | — | Difference 24 |
| | | | | | (or 8 if value * is omitted) |
| 6 | D | Gray | 164 | — | Average (*a*) 167·4 |
| | A | Pensky, M. | 169 | 170 | Average (*b*) 167·4 |
| | C | Gray | 165·5 | — | Maximum 170 |
| | E | Pensky, M. | 168 | — | Minimum 164 |
| | B | Gray | 170 | — | — |
| | F | — | 165 | — | Difference 6 |
| 7 | D | Gray | 185 | — | Average (*a*) 182·3 |
| | A | Pensky, M. | 188 | — | Average (*b*) 183·5 |
| | C | Gray | 185 | — | Maximum 188 |
| | E | Pensky, M. | 183 | — | Minimum 181 |
| | B | Gray | 181 | 182 | — |
| | F | — | 187 | — | Difference 7 |
| 8 | D | Gray | 168 | — | Average (*a*) 167·2 |
| | A | Pensky, M. | 168 | 171 | Average (*b*) 167·2 |
| | C | Gray | 165·5 | — | Maximum 171·0 |
| | E | Pensky, M. | 168 | — | Minimum 163·3 |
| | B | Gray | 163·3 | — | — |
| | F | — | 167 | — | Difference 7·7 |
| 9 | D | Gray | 172 | — | Average (*a*) 172·9 |
| | A | Pensky, M. | 173 | — | Average (*b*) 172·9 |
| | C | Gray | 175·5 | — | Maximum 175·5 |
| | E | Pensky, M. | 173 | — | Minimum 171·0 |
| | B | Gray | 171 | — | — |
| | F | — | 173 | — | Difference 4·5 |
| 10 | D | Gray | 132 | — | Average (*a*) 131·3 |
| | A | Pensky, M. | 132 | 133 | Average (*b*) 131·8 |
| | C | Gray | 128* | — | Maximum 133 |
| | E | Pensky, M. | 133 | — | Minimum 128 |
| | B | Gray | 131 | — | — |
| | F | — | 130 | — | Difference 5 |
| | | | | | (or 3 if value * is omitted) |

Average: (*a*) = Gross ; (*b*) = Selected.

NOTE.—Investigator D definitely states that he used standardized thermometers.

Investigator A does not specifically mention this fact.

Investigator C recommends standard thermometers, but does not state that they were used.

Investigator E states that his values are the means of several tests, but omits to state specifically if standardized thermometers were used.

Investigator B used standardized thermometers, which had been in use some years since standardization ; they were not specially re-standardized for this research.

Investigator F makes no comments.

* These results are obviously incorrect.

taken, also those suggested by the National Physical Laboratory's work, detailed by Dr. Harker and W. F. Higgins (Collected Researches, vol. 8).

Whenever petroleum spirits or similar low-flash-point solvents are used for washing out the oil cup of flash-point apparatus, it is most necessary to put the oil cup into a well-ventilated oven which is maintained at 120° C. and to keep it there for about 30 minutes in order to drive off thoroughly all traces of these cleansing solvents, otherwise they will cause abnormally low flash-point results when the apparatus is next used.

The differences between the results reported (Table 4) are in some cases excessive. By an oversight no inter-comparison of the thermometers of the various instruments used was made prior to the commencement of the research. If such comparison had been instituted it is likely that the agreement would have been much better. However, the results as they stand are probably indicative of the quality of work and degree of agreement usually attained in commercial testing.

### Test No. 4 : Viscosity at Different Temperatures.

Table 5 gives the maximum, minimum and average viscosity of the various oils tested at different temperatures.

Table 5.

*Test No. 4 ; Viscosity at Different Temperatures.*

Time of Efflux of 50 cm³ of Oil, in Seconds, using Standard Redwood Viscometers.

| Oil No. | | Temperatures (Centigrade and Fahrenheit) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 15·5° C. 60° F. | 30° C. 86° F. | 32·2° C. 90° F. | 35° C. 95° F. | 37·7° C. 100° F. | 50° C. 122° F. | 65° C. 149° F. | 65·5° C. 150° F. | 80° C. 176° F. | 90° C. 194° F. |
| | | *Times of Efflux, in Seconds.* | | | | | | | | | |
| 1 | Maximum | 308·3 | — | — | — | — | 67·2 | 50·0 | — | 42·0 | — |
| | Minimum | 286·0 | — | — | — | — | 63·0 | 47·9 | — | 38·0 | — |
| | Average | 305·3 | 145 | 123·0 | 106·2 | 102 | 64·9 | 48·9 | — | 40·1 | 37 |
| 2 | Maximum | 350·0 | — | — | — | — | 71·0 | 50·0 | — | 42·0 | — |
| | Minimum | 309·0 | — | — | — | — | 64·7 | 48·6 | — | 39·0 | — |
| | Average | 314·3 | 149 | — | 110·0 | 104 | 67·5 | 49·3 | — | 40·3 | 36 |
| 3 | Maximum | 1 268·2 | — | — | — | — | 165·0 | — | — | 60·4 | — |
| | Minimum | 1 190·0 | — | — | — | — | 155·0 | — | — | 58·3 | — |
| | Average | 1 222·7 | — | 398·5 | 314·0 | 307 | 159·5 | 89·0 | 87·0 | 59·6 | — |
| 4 | Maximum | 502·0 | — | — | — | — | 90·0 | — | — | 47·0 | — |
| | Minimum | 478·0 | — | — | — | — | 85·0 | — | — | 44·1 | — |
| | Average | 495·4 | — | 189·0 | 162·0 | 148 | 87·2 | 58·8 | 58·5 | 45·5 | — |
| 5 | Maximum | 442·0 | — | — | — | — | 92·0 | — | — | 47·1 | — |
| | Minimum | 400·0 | — | — | — | — | 80·0 | — | — | 46·0 | — |
| | Average | 422·9 | — | 175·0 | 152·8 | 141 | 89·5 | 60·0 | 58·7 | 46·9 | — |
| 6 | Maximum | 475·0 | — | — | — | — | 84·0 | 55·0 | — | 49·0 | — |
| | Minimum | 394·0 | — | — | — | — | 79·0 | 54·3 | — | 42·6 | — |
| | Average | 421·5 | 184 | 167·0 | 142·6 | 125 | 80·8 | 54·6 | — | 43·5 | 39 |
| 7 | Maximum | 317·5 | — | — | — | — | 72·5 | 52·0 | — | 42·5 | — |
| | Minimum | 276·0 | — | — | — | — | 66·0 | 50·6 | — | 40·0 | — |
| | Average | 294·5 | 142 | 127·0 | 113·0 | 100 | 68·8 | 51·3 | 50·5 | 41·4 | 38 |
| 8 | Maximum | 155·0 | — | — | — | — | 54·0 | — | — | 37·6 | — |
| | Minimum | 150·0 | — | — | — | — | 49·0 | — | — | 36·7 | — |
| | Average | 152·9 | — | — | 71·0 | 65 | 51·1 | 41·8 | 42·0 | 37·4 | — |
| 9 | Maximum | 155·0 | — | — | — | — | 52·0 | — | — | 31·0 | — |
| | Minimum | 148·0 | — | 78·5 | — | — | 50·5 | — | — | 30·0 | — |
| | Average | 151·5 | — | 78·5 | 70·4 | 69 | 51·3 | 41·8 | 41·7 | 37·4 | — |
| 10 | Maximum | 57·3 | — | — | — | — | 35·4 | — | — | 31·0 | — |
| | Minimum | 51·0 | — | — | — | — | 34·8 | — | — | 30·0 | — |
| | Average | 53·0 | — | 40·4 | 39·1 | 38 | 35·0 | 32·0 | 32·4 | 30·3 | — |

The three temperatures stipulated were 15·5° C., 50° C. and 80° C., but some of the experimenters made tests at additional temperatures in order to obtain better curves. From the average values the curves in Fig. 3 have been drawn.

With the exception of the results for the lowest temperature (15·5° C.) the agreement between the various experimenters is satisfactory.

The differences cover all variables likely to be met

TABLE 6.

*Test No.* 5c ; *Iodine Absorption Value* (*Hübl's Process*).

Weight of Sample used : 1·0 to 1·25 g in 10 cm³ Chloroform. Standard Iodine Solution used : 50 cm³. Duration of reaction : 18 to 24 hours.

| Oil No. | Investigator A | Investigator C | Investigator E | Investigator B | Investigator F | Summary | | |
|---|---|---|---|---|---|---|---|---|
| | Percentage iodine absorption, by weight | | | | | Maximum | Minimum | Average, excluding * |
| | Per cent | Per cent | Per cent | Per cent | Per cent | Per cent | Per cent | Per cent |
| 1 | 10·0 | 9·83 | 8·4* | 11·1 to 11·2 | not done | 11·2 | 8·4 | 10·58 |
| 2 | 10·5 | 10·37 | 8·0* | 11·0 to 11·76 | not done | 11·76 | 8·0 | 10·90 |
| 3 | 0·4 | 0·86 | 1·0 | 0·51 to 0·53 | 0·72 | 1·0 | 0·4 | 0·67 |
| 4 | 0·4 | 0·88 | 0·6 | 0·32* to 0·60 | 0·72 | 0·88 | 0·32 | 0·64 |
| 5 | 9·2* | 11·4 | 11·3 | 12·3 to 12·71* | 13·00* | 13·0 | 9·2 | 11·7 |
| 6 | 1·3 | 1·33 | 1·2 | 1·27 to 1·54 | 1·58 | 1·58 | 1·2 | 1·37 |
| 7 | 0·2 | 0·44 | 0·3 | 0·12* to 0·18 | 0·49 | 0·49 | 0·12 | 0·32 |
| 8 | 15·1 | 15·0 | 14·7 | 15·12 to 16·53* | 15·16 | 16·53 | 14·7 | 15·01 |
| 9 | 1·1 | 1·42 | 1·3 | 1·03 to 1·40 | 2·60* | 2·60 | 1·03 | 1·25 |
| 10 | 9·4 | 10·1 | 9·6 | 9·88 to 10·67 | 10·54 | 10·67 | 9·4 | 10·03 |

NOTE.—The large variation in results for Sample 5 is probably largely connected with the *condition* of this oil. It was oil which had been in use and was not very clean. In order to show that individual operators get fair agreement in their own tests, the full set of results found for this oil by investigator B are given below :—

Oil No. 5 : 12·59, 12·48, 12·40, 12·30, 12·69, 12·71. Maximum 12·71, minimum 12·30, difference 0·71, average 12·53.

* These results are obviously incorrect.

with in general work, viz. differences in thermometers, the jets and other dimensions of the viscometers, measuring flasks, stop-watches and the personal equation.

TEST NO. 5 : CHEMICAL REACTIONS.

(*a*) *Acidity and* (*b*) *Alkalinity*.—Results of the acidity and alkalinity tests proved that these oils were pure and free from injurious quantities of either acids or alkalis. These two tests are of a purely precautionary value. Normally there should be no reaction, and even in old stock the reactions should not show more than the equivalent of 2 to 3 mg of caustic potash (KOH) per gramme of oil. The tests therefore will show up any carelessness which has occurred in the oil refinery.

To prevent imperfectly purified oils being used, these tests are proposed as part of all specifications. They also form checks upon the behaviour of the oils during use, because they will indicate whether :—

(i) The sludging is producing undesirable amounts of acidity, and the rate of its formation, or

(ii) If the oil is dissolving acid-resinous and free-acid bodies from insulations or paints which have been used in the construction of the apparatus.

(*c*) *Iodine absorption value* (*Hübl's process*).

*Results of tests*.—Only five experimenters undertook this test. The results are shown in Table 6.

*Consideration of results*.—The results confirm the opinion that there is a distinct practical and chemical relationship between the iodine value of an oil and its sludging propensity under commercial conditions of use. The relation is far more clearly traced when the sludging has been performed when using air than when employing oxygen (see Fig. 2).

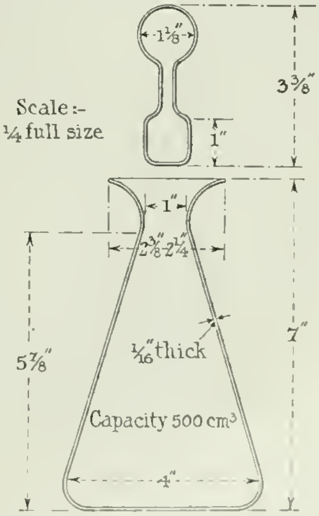


FIG. 4.—Conical flask for determination of iodine values.

This test is of value as providing an alternative rough check of oil deliveries with respect to their sludging qualities.

The iodine value can be determined by the Hübl method in 18 to 24 hours as against 72 to 80 hours for the completion of the sludging test (i.e. before the weight of the separated and dried sludge can be obtained).

It is recommended that the form and size of the flasks used for this test be made standard, and the inexpensive but efficient flask shown in Fig. 4 is recommended.

### Test No. 6a : Density.

Although the density test as carried out is primarily simple, yet there are several possible sources of error, and the small differences (not exceeding a maximum difference of 0·4 per cent from the mean) found in the results were probably due to incorrect temperature control.

The special importance of correct results for the density arises from the fact that the data obtained were required for the calculation of the coefficient of thermal expansion.

Table 7.

*Test No. 6a ; Density at Different Temperatures, compared with that of Pure Water at the Same Temperatures.*

| Oil No. | Temperatures (Centigrade and Fahrenheit) | | | | | |
|---|---|---|---|---|---|---|
| | 15·5° C.<br>60° F. | 21·1° C.<br>70° F. | 26·6° C.<br>80° F. | 32·2° C.<br>90° F. | 50° C.<br>122° F. | 80° C.<br>176° F. |
| | Average density (water at same temperature = 1) | | | | | |
| 1 | 0·9159 | — | — | — | 0·8938 | 0·8740 |
| 2 | 0·9170 | — | — | — | 0·8942 | 0·8750 |
| 3 | 0·8913 | — | — | — | 0·8698 | 0·8513 |
| 4 | 0·8839 | — | — | — | 0·8618 | 0·8424 |
| 5 | 0·8683 | — | — | — | 0·8474 | 0·8286 |
| 6 | 0·8822 | 0·879 | — | — | 0·8606 | 0·8424 |
| 7 | 0·8610 | 0·858 | 0·854 | — | 0·8388 | 0·8206 |
| 8 | 0·8603 | 0·857 | 0·854 | 0·850 | 0·8378 | 0·8182 |
| 9 | 0·8446 | 0·842 | 0·838 | 0·834 | 0·8227 | 0·8037 |
| 10 | 0·8271 | 0·824 | 0·821 | 0·817 | 0·8041 | 0·7846 |

### Test No. 6b : Coefficient of Volumetric Expansion.

*Method of test.*—This determination required accurate specific gravity determinations of the oils at different temperatures, and the use of the following formula in conjunction with figures from Table 41a on page 212, vol. 1 of "Physico-Chemical Tables" by J. Castell Evans.

$$a = \frac{Vt_1 - Vt}{Vt(t_1 - t)}$$

where $a$ = coefficient of expansion;
$t$ = lower temperature taken;
$t_1$ = higher temperature taken;
$V$ = volume.

Or $$a = \frac{d - d_1}{d_1(t_1 - t)}$$

where $a$ = coefficient of expansion;
$d$ = density at the lower temperature ($t$);
$d_1$ = density at the higher temperature ($t_1$).

*Results of tests.*—The results are given in Table 8. In most cases the mean expansion alone was reported.

Table 8.

*Test No. 6b ; Coefficient of Volumetric Expansion.*

| Oil No. | Investigator | Temperature of experiment | | |
|---|---|---|---|---|
| | | 15·5° C. to 50° C.<br>60° F. to 122° F. | 50° C. to 80° C.<br>122° F to 176° F. | 15·5° C. to 80° C.<br>60° F. to 176° F. |
| 1 | A | — | — | 0·000754 |
| | C | 0·000707 | 0·000732 | 0·000720 |
| | E | — | — | 0·000756 |
| 2 | A | — | — | 0·000749 |
| | C | 0·000746 | 0·000669 | 0·000707 |
| | E | — | — | 0·000756 |
| 3 | A | — | — | 0·000732 |
| | C | 0·000693 | 0·000652 | 0·000672 |
| | E | — | — | 0·000731 |
| | F | — | — | 0·000746 |
| 4 | A | — | — | 0·000754 |
| | C | 0·000729 | 0·000707 | 0·000718 |
| | E | — | — | 0·000769 |
| | F | — | — | 0·000753 |
| 5 | A | — | — | 0·000769 |
| | C | 0·000691 | 0·000641 | 0·000666 |
| | E | — | — | 0·000784 |
| | F | — | — | 0·000780 |
| 6 | A | — | — | 0·000753 |
| | C | 0·000683 | 0·000752 | 0·000717 |
| | E | — | — | 0·000767 |
| | F | — | — | 0·000724 |
| 7 | A | — | — | 0·000784 |
| | C | 0·000796 | 0·000722 | 0·000758 |
| | E | — | — | 0·000780 |
| | F | — | — | 0·000789 |
| 8 | A | — | — | 0·000795 |
| | C | 0·000726 | 0·000802 | 0·000764 |
| | E | — | — | 0·000801 |
| | F | — | — | 0·000842 |
| 9 | A | — | — | 0·000808 |
| | C | 0·000732 | 0·000812 | 0·000772 |
| | E | — | — | 0·000793 |
| | F | — | — | 0·000719 |
| 10 | A | — | — | 0·000859 |
| | C | 0·000810 | 0·000867 | 0·000838 |
| | E | — | — | 0·000853 |
| | F | — | — | 0·000793 |

*Consideration of results.*—As noted under the heading "Density Test," the main cause of the discrepancy between the reports is probably due to insufficient care in temperature control and the utilization of glass apparatus.

Very few good data exist respecting the volumetric expansion of refined oils. The data published in textbooks and treatises refer mainly to crude oils or imperfectly refined oils of the lubricating oil type, and such data cannot be considered to hold good for the highly refined modern products used for insulating oils; therefore the data obtained by the Association are of special value.

Quartz vessels may be used with advantage for the experiments, and special care must be taken to control the temperature with very close accuracy.

### Test No. 7 : Cold Test (Solidification).

*Methods of test.*—The results for this test obtained by using the original method of the Electrical Research Committee proved more discordant than was anticipated. The general conclusion of the investigator was that consistent results were not obtained by this method because a good deal depends upon the rate of stirring.

Table 9.

*Test No. 7 ; Cold Test (Archbutt's Method).*

| Oil No. | Solidification temperature, | | |
|---|---|---|---|
| | Investigator A | Investigator B | Investigator C |
| 1 | + 6·5° C. | 0° C. solid<br>Re-liquefied + 4·5° C. | + 2·5° C. |
| 2 | + 7·0° C. | 0° C.<br>Re-liquefied + 4·5° C. | + 2·5° C. |
| 3 | not done | — 19° C.<br>Re-liquefied — 13° C. | — 16·6° C. |
| 4 | not done | not done | below — 17·7° C. |
| 5 | — 2·0° C. | — 4·5° C.<br>Re-liquefied — 3° C. | — 8·3° C. |
| 6 | not done | below — 24° C. | below — 17·7° C. |
| 7 | — 13° C. | — 13·5° C.<br>Re-liquefied — 11° C. | below — 17·7° C. |
| 8 | — 8·8° C. | — 13·5° C.<br>Re-liquefied — 10° C. | — 15° C. |
| 9 | — 5° C. | — 4·25° C.<br>Re-liquefied — 3·0° C. | — 11·9° C. |
| 10 | — 4° C. | — 4·45° C.<br>Re-liquefied — 3·5° C. | — 3·8° C. |

Much more consistent results were obtained by cooling the oil and gently stirring with the thermometer until within a degree or two of the solidifying point or the temperature at which solid matter separates out, and then allowing the oil to cool further very slowly and without stirring, until the oil will no longer flow in the tube.

As a result of the discussions in Committee it was decided to use an older method which is known as the Archbutt method and is described in "Lubrication and Lubricants" by L. Archbutt and R. M. Deeley [Chas. Griffin and Co., London].

*Consideration of results.*—The results obtained are given in Table 9 and show some improvement upon those obtained by the original E.R.C. method. But so much depends upon the personal equation that agreement within ± 5° C. is as much as can be expected with any form of cold test. This partly arises from the necessity of defining the setting point in terms of viscosity, which is practically what a cold test amounts to.

Insulating oils are not pure substances, but variable mixtures of many homologous substances of two or three different homologous series of chemical substances (hydrocarbons), each member possessing its own true and definite solidification temperature—some higher and some lower than the average of the series present. There is therefore no sharp solidification temperature or setting point for mineral oils, but a range of temperatures over which the oil gradually becomes more and more solid and at last appears to be too solid to flow.

The oil is not necessarily solid throughout its mass at the temperature at which it will not flow along an inclined test-tube. It is usually only partly solidified.

The differences noted between the results of different experimenters bear testimony to the real difficulty of devising a satisfactory Cold Test for such materials as insulating oils.

It was finally decided to recommend the adoption of the Archbutt method because it had already attained considerable status and had been used for several years in connection with oil, fat and wax industries.

### Test No. 12 : Specific Heat.

*Method of test.*—Tests on the specific heats of transformer oils were carried out by two investigators. In both cases the electrical method was employed. The oil was stirred throughout the experiment and the necessary corrections for cooling were applied in each case.

*Results of tests.*—Both investigators obtained values in the neighbourhood of air temperature, while one gave figures for the specific heat in the neighbourhood of 47° C. and the other examined four of the oils over the range 15° C. to 80° C., in which latter case the oils were dried prior to test.

Tables 10 and 11 give the results obtained.

Table 10.

*Specific Heat.*

| Oil No. | Investigator A | | | | Investigator G | |
|---|---|---|---|---|---|---|
| | Mean Temp. | Specific Heat | Mean Temp. | Specific Heat | Mean Temp. | Specific Heat |
| | ° C. | | ° C. | | ° C. | |
| 1 | 19·1 | 0·425 | 47·6 | 0·453 | 15·5 | 0·422 |
| 2 | 17·0 | 0·429 | 46·7 | 0·455 | 15·5 | 0·427 |
| 3 | 17·4 | 0·442 | 46·7 | 0·469 | 15·5 | 0·431 |
| 5 | 16·8 | 0·457 | 47·6 | 0·481 | 15·5 | 0·458 |
| 6 | 16·2 | 0·437 | 46·3 | 0·471 | 15·5 | 0·433 |
| 7 | 19·3 | 0·454 | 47·6 | 0·484 | 15·5 | 0·460 |
| 8 | 16·8 | 0·457 | 47·5 | 0·482 | 15·5 | 0·452 |
| 9 | 15·7 | 0·466 | 47·4 | 0·495 | 15·5 | 0·457 |
| 10 | 17·1 | 0·469 | 46·8 | 0·494 | 15·5 | 0·469 |

*Consideration of results.*—It will be seen that both observers give results in reasonable agreement at the lower temperatures, but at the higher temperatures greater discrepancies are noted. This is probably partly due to the method of measurement.

The differences between the values for the different oils were not so great that the value of the specific heat needed to be taken into account in drawing up a specification.

TABLE 11.

*Specific Heat (Investigator G).*

| Oil No. | Specific Heats at mean temperatures of | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 15·5° C. | 20° C. | 30° C. | 40° C. | 50° C. | 60° C. | 70° C. | 80° C. |
| 1 | 0·427 | 0·454 | 0·467 | 0·486 | 0·497 | 0·498 | 0·502 | 0·508 |
| 5 | 0·457 | 0·469 | 0·489 | 0·503 | 0·518 | 0·532 | 0·540 | 0·538 |
| 7 | 0·455 | 0·468 | 0·469 | 0·482 | 0·497 | 0·496 | 0·510 | 0·525 |
| 8 | — | — | — | — | 0·500 | 0·514 | 0·529 | 0·529 |

*Specific heat of unit volume.*—Table 12 gives the specific heat of unit volume of each oil, and shows that within experimental error it has a constant value of 0·390 at about 15·5° C. Investigation also showed that at 50° C. the specific heat of unit volume is constant at 0·405.

TABLE 12.

*Specific Heat of Unit Volume.*

| Oil No. | Mean specific heat | Density at 15·5° C. | Specific heat of unit volume |
|---|---|---|---|
| 1 | 0·425 | 0·916 | 0·390 |
| 2 | 0·430 | 0·917 | 0·395 |
| 3 | 0·435 | 0·891 | 0·390 |
| 5 | 0·455 | 0·868 | 0·395 |
| 6 | 0·435 | 0·882 | 0·385 |
| 7 | 0·460 | 0·861 | 0·395 |
| 8 | 0·455 | 0·860 | 0·390 |
| 9 | 0·460 | 0·845 | 0·390 |
| 10 | 0·470 | 0·827 | 0·390 |

## LATENT HEAT OF VAPORIZATION.

*Features investigated.*—For the purposes of this inquiry it was necessary to measure the quantity of heat required to convert unit mass of oil from liquid to vapour at its boiling point, rather than the heat given out on condensation of the vapour to liquid.

*Description of apparatus.*—A special apparatus (shown diagrammatically in Fig. 5) was designed for these experiments. It consists essentially of a vacuum-walled vessel supported in an enclosure the temperature of which is maintained the same as that of the interior of the vacuum vessel. Thus any heat loss or gain by the oil in the vessel during the test is eliminated.

The flask is about half filled with the oil, in which a platinum heating coil is totally immersed. The vessel is closed by a metal cover fitting loosely into an annular channel on the top of the flask, and a seal is effected by flooding this channel with molten tin at high temperatures, and mercury at low temperatures. A mica disc fits down on the top edge of the vessel, so that the vapour rising from the oil does not come into direct contact with the metal cover; the hollow cover thus constitutes a heat-insulating air space. A thermometer and copper/constantan thermo-junction are introduced through packing glands in the cover.

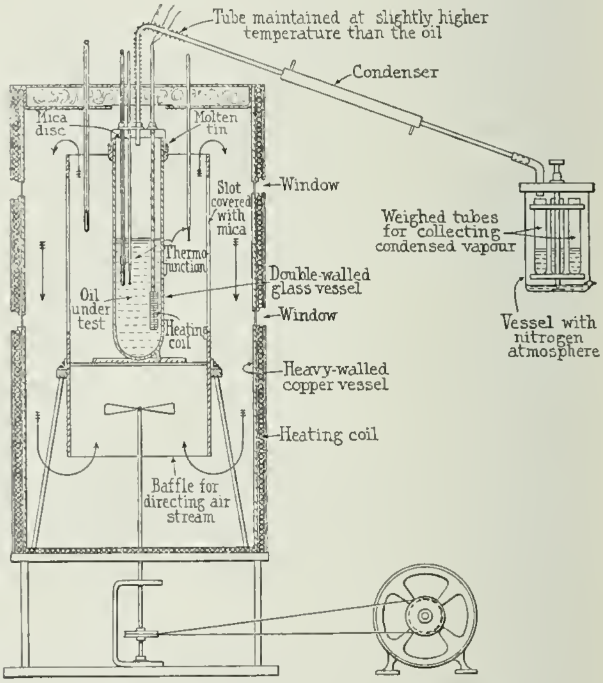

Tube maintained at slightly higher temperature than the oil
Condenser
Mica disc
Molten tin
Slot covered with mica
Window
Weighed tubes for collecting condensed vapour
Thermo junction
Double-walled glass vessel
Oil under test
Window
Heating coil
Vessel with nitrogen atmosphere
Heavy-walled copper vessel
Heating coil
Baffle for directing air stream

FIG. 5.—Apparatus for determining latent heat.

*Method of test.*—The flask is totally enclosed in a copper cylinder the exterior surfaces of which are wound with a heating coil of constantan wire. Throughout the experiments the temperature of the air within this jacket was maintained the same as that of the oil in the vacuum vessel by adjustment of the current flowing through the heating coil on the jacket. Equalization of the temperature in the interior was effected by means of the fan and baffle shown in Fig. 5. The fan forced the air up past the surface of the flask and down along the surface of the outer cylinder. By the use of a differential thermo-junction, one junction of which was in the oil and the other in the air space, equality of temperature could be maintained by observing the deflections of the galvanometer connected in the circuit of the differential thermo-junction.

The vapour was led away from the flask through a tube heated by a coil to a temperature slightly above the boiling point of the oil. Thus no condensation could occur in the vertical limb of the tube and no liquid dropped back into the interior of the flask. This leading-off tube was cooled beyond the bend, over a length of about 12 inches, by water circulation. The condensed oil was collected in weighed test-tubes, a series of which were set up in an atmosphere of nitrogen.

For observational purposes windows were cut in the outer jacket and the baffle, so that the observer could see precisely the effect of the heating on the oil. It was observed that the evolution of vapour started and ceased instantaneously with the switching on and off of the electrical supply when the oil was at its boiling point. A number of experiments were made using varied amounts of energy, a 5-fold change in the electrical supply being made in the course of a series of experiments. The results obtained were in close agreement, so that it could be assumed that the apparatus was functioning quite satisfactorily.

*Results of tests.*—The results obtained on seven oils are summarized in Table 13. These results were roughly checked by measuring the heat given out when the oil vapour was condensed in a calorimeter.

TABLE 13.

*Latent Heat.*

| Oil No. | Temperature | Latent heat, in gramme-calories |
|---|---|---|
| | ° C. | |
| 2 | 372 | 82 |
| 8 | 358 | 47 |
| 9 | 370 | 47 |
| 10 | 307 | 89 |
| (*a*) | 397 | 70 |
| (*b*) | 385 | 52 |
| (*d*) | 370 | 68 |

## VAPOUR PRESSURES.

The vapour pressure of oils had apparently not been previously investigated, although this constant had been determined for a number of pure hydrocarbons. The exact physical interpretations of experimental results would be complicated by the fact that ordinary oils are mixtures of a number of components of different boiling points, but the tests should throw some light upon present methods of determining rates of evaporation.

*Method of test.*—Measurements of the vapour pressures were carried out over the range 60° C. to 140° C. A variety of methods was employed, that finally adopted being one in which a little of the oil was introduced into the vacuum above a barometer column the undisturbed height of which was previously noted. The temperature of the upper part of the tube was then raised by means of a jacket through which some suitable vapour was circulated. When conditions were steady, the height of the mercury column was again noted. The difference between this and the original height, due to the pressure of the vapour of the oil, was corrected to 0° C. (since part of the mercury column was at

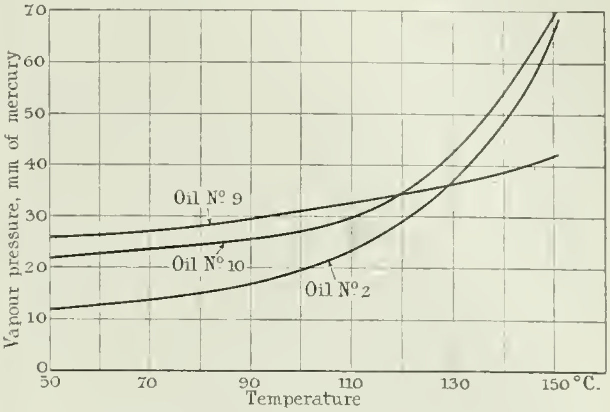


FIG. 6.—Relation between vapour pressure and temperature.

TABLE 14.

*Vapour Pressures.*

| Temperature | Vapour pressure in mm of mercury | | |
|---|---|---|---|
| | Oil No. 2 | Oil No. 9 | Oil No. 10 |
| ° C. | | | |
| 50 | 12 | 25 | 22 |
| 60 | 13 | 26 | 23 |
| 70 | 14 | 27 | 24 |
| 80 | 15 | 28 | 25 |
| 90 | 17 | 29 | 26 |
| 100 | 20 | 30 | 27 |
| 110 | 24 | 32 | 30 |
| 120 | 29 | 34 | 35 |
| 130 | 38 | 37 | 43 |
| 140 | 49 | 39 | 55 |
| 150 | 68 | 41 | 72 |

the high temperature and part at that of the air). A further correction was made for the vapour pressure of the mercury, which at the higher temperatures is quite appreciable.

The heights were read to the nearest 0·5 mm and the pairs of readings taken at each temperature are usually accordant to within this limit. No correction was considered necessary for capillarity nor for the pressure exerted by the unevaporated portion of the oil, as the quantity used was only just sufficient to cover the surface of the mercury at the temperature of the experiment.

*Results of tests.*—The results of the experiments are shown in the curves (Fig. 6) and in Table 14, which gives the vapour pressure of each oil over the range from 50° C. to 150° C. in steps of 10 degrees.

*Consideration of results.*—The general form of the curves is that usually found for vapour pressures, increasing slowly at first and with greater rapidity at higher temperatures. One of the three oils (No. 9) has an unusually "flat" curve over the range studied.

Referring to the report on the latent heat of vaporization of these oils (see page 672), it will be seen that this sample gave a very low value, viz. 47, compared with 82 and 89 gramme-calories for oils Nos. 2 and 10 respectively. The low value of the vapour pressure associated with low latent heat for No. 9 is significant, and further information as to the nature of the oil might be of value in affording an explanation of these results.

It will be noted that in no case is the vapour pressure at 150° C. greater than about 70 mm mercury (less than 1/10th atmospheric pressure) so that, for example, the pressure at 150° C. in an enclosed space containing oil would be only $1\frac{1}{2}$ lb. per sq. in. above atmospheric pressure.

### THE ACTION OF CATALYSERS.

*Features and materials investigated.*—The purpose of this investigation, which was intended to be of a preliminary character, was to ascertain qualitatively the action on insulating oils of those metals and catalysers which are commonly used or may reasonably be expected to be used in the construction of oil switches and transformers. It was known that the character of the sludge varied with the catalyser, that some metals have a serious effect on the amount of sludging, and that under certain conditions, not yet analysed, the sludge produced may have a bad effect on a switch.

The oils used were Nos. 2, 6 and 9. The action on these oils of 17 different materials (kindly supplied for the purpose by the B.T.H. Co., Ltd.) was tried.

The metals were in the form of sheet, and the total area exposed to the oil was $2\frac{1}{2}$ sq. in.

In the case of the powdered materials 0·05 g was used in each case.

*Method of test.*—Preliminary tests showed that in order to obtain any very definite results in a reasonable time it would be necessary to work at a temperature not under 100° C., and accordingly this temperature was chosen. After 500 hours' heating the beakers were removed from the oil bath and the appearance of the oils was noted. The oils were then diluted with twice their volume of petroleum spirit, allowed to stand for 24 hours, and the deposits were then weighed.

*Results of tests.*—In all cases the oil had darkened in colour, the darkening being roughly proportional to the amount of deposit formed.

No. 2 oil darkened very considerably, and in this case a test without the addition of any catalyser gave a weighable quantity of deposit. Of the metals, precipitated copper was the most active, then lead and strip copper and the copper alloys. The other metals showed practically no action on any of the oils. Of the other materials used, litharge showed a very pronounced action on No. 2 oil. In all cases the deposits were of a powdery nature, with the exception of No. 9 oil, where the deposits were of a sticky nature.

The figures in Table 15 represent the weight of solid matter in grammes obtained from 50 cm³ of oil.

TABLE 15.

*Action of Catalysers.*

| Metals or catalysers used | Oil No. 2 | Oil No. 6 | Oil No. 9 |
|---|---|---|---|
| Litharge | 0·80 | 0·14 | 0·05 |
| Cobalt acetate | 0·22 | 0·05 | 0·05 |
| Manganese resinate | 0·12 | 0·18 | 0·05 |
| Lead | 0·09 | 0·03 | 0·01 |
| Aluminium pure strip (British Aluminium Co.) | 0·04 | — | — |
| Cobalt pure strip (Henry Wiggin & Co.) | 0·04 | — | — |
| Nickel, pure (Henry Wiggin & Co.) | 0·06 | — | — |
| Zinc, pure | 0·04 | — | — |
| Iron, pure ("Armco Brand") | 0·05 | — | — |
| Gun-metal; cast Cu 88 %, Sn 10 %, Zn 2 % | 0·12 | trace | — |
| Copper strip, pure electrolytic | 0·08 | trace | — |
| Copper precipitate | 0·31 | trace | trace |
| Brass 60/40 hard strip | 0·11 | trace | — |
| Brass 70/30 | 0·14 | trace | — |
| Tin Babbitt, cast, Sn 83·3 %, Sb 8·4 %, Cu 8·5 % | 0·05 | — | — |
| Lead Babbitt (Hoyt metal), cast, Pb 77 %, Sb 14 %, Sn 9 % | 0·05 | — | — |
| Tin/lead solder: 50/50 Sn, Pb | 0·04 | — | — |
| Blank | 0·04 | — | — |

*Conclusions.*—In view of the above results it was concluded that dryers containing lead or cobalt, or manganese resinates or acetates, are liable to increase the quantity of sludge formed by an oil. For this reason paints or varnishes containing these dryers should be reduced to a minimum if employed at all.

# POWER FACTOR: ITS TECHNICAL AND COMMERCIAL ASPECTS.

By H. E. YERBURY, Member.

(*Paper first received* 17*th October, and in final form* 15*th December*, 1922; *read before the* SHEFFIELD SUB-CENTRE 17*th January, and before the* NORTH MIDLAND CENTRE 6*th March*, 1923.)

### SUMMARY.

The author submits that the highest possible efficiency of an electrical undertaking can only be attained by studying all the factors which at present militate against a low selling price per unit. The low average power factor existing on many undertakings could be raised, and consumers should be encouraged to improve their power factor by the establishment of a principle of granting a rebate for a high power factor.

It is considered that a kVA charge plus a kWh charge is more equitable to power suppliers and consumers than a pure kWh basis of charge, and, now that the 1922 Act provides for a kVA basis at the option of any supplier, it is felt that a change should be made as soon as possible.

Consumers should be educated and advice given gratuitously by a supply department so that the most suitable plant may be installed in order to obtain the highest all-round efficiency. By increasing the average power factor on any a.c. system the capital expenditure on generating, transforming and distribution plant, and also energy losses, can be considerably reduced to the advantage of both supplier and consumer.

Power-factor-correcting apparatus is now on the market and is suitable for all requirements. Each type should be considered on its merits for every installation. The selling price of electrical energy per unit should be reduced on an improvement of power factor, and increased where it falls below a pre-determined standard.

### INTRODUCTION.

This paper has not been written with the intention of dealing with the fundamental laws of alternating currents and the properties of a.c. circuits, nor to show graphically or diagrammatically the production and effect of lagging power factor, as most engineers are familiar with vector diagrams, etc.

The purpose of the paper will be served if it results in the consideration of the reasons for the low power factor in machines and apparatus as commonly used, the means that are available at the present time for improving the existing conditions, and what can be accomplished in the reduction of charges as affecting the supplier and consumer.

Although the subject must necessarily be elementary and platitudinous in character, it is hoped that a frank and impartial discussion will result, and that arguments will be forthcoming against the continuance of the present general kWh basis of charge.

Fig. 1 shows the relation between energy load, kilovolt-amperes and power factor of the usual percentages found in everyday experience in a general supply system.

The effect of load factor is well known to all station engineers, and many published official statistics contain figures on the matter, but the effect of power factor appears to assume a place of secondary importance to many suppliers and users of electrical energy. In the early days of the industry the supplier was only too pleased to connect any apparatus which brought revenue to the department, irrespective of whether such connection was conducive to the efficiency of his plant. Now that capital charges and works costs have to be seriously studied in order to produce an attractive and low selling price of electricity, especially to large consumers such as railway companies, tramways, rolling mills and steel melters, etc., it is believed that no more useful field can be explored than the production of a reasonably high power factor and the savings that would accrue therefrom.

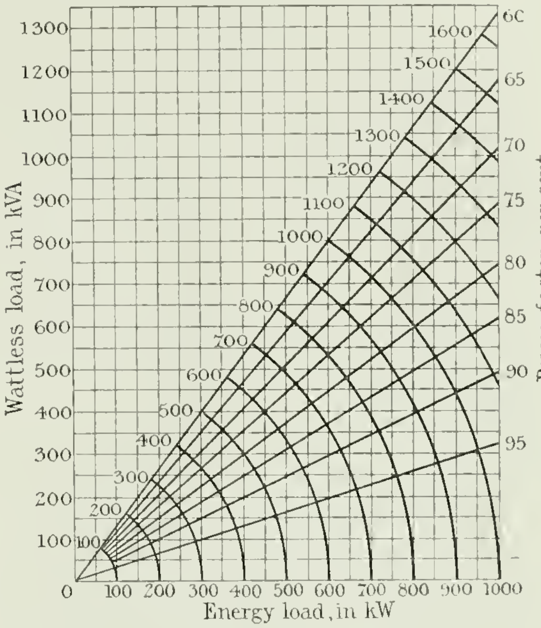


FIG. 1.—Curves showing the total load in kVA.

### INFLUENCE OF POWER FACTOR ON COSTS.

In order to impress forcibly on the mind what power factor really means, as compared with a direct-current supply where such a term is inapplicable, let us consider a specific instance of a town with two power stations, one having a plant capacity of 80 000 kW and the other a capacity of 20 000 kW.

Let us assume these two stations to be interconnected by duplicate cables, each capable of carrying a load of 5 000 kW.

By adjusting the field strength of the generators, wattless kilovolt-amperes can be made to flow around the circuit of the generators and interconnecting cables, and energy may be transmitted from one station to the other.

Assuming the power factor of the entire undertaking to be 0·8, if this could be raised to unity the smaller station could be dispensed with, or would be available for supplying energy to additional consumers taking up to at least 15 000 kW and bringing in a net return of at least £1 500 per annum.

A station of that capacity represents a capital expenditure of about £450 000.

A power factor of 0·8 calls for a 25 per cent increase in the number of kilovolt-amperes, which means that the capacity of generators, transformers and cables, etc., must, for the same revenue-earning load, be increased in this percentage. An improvement in power factor from the present general average of 0·7 to 0·9 would produce a 30 per cent greater revenue-earning capacity for the same plant. It will therefore be readily seen that power factor has a very great influence on the cost, and therefore the selling price of electricity and every aspect of the matter is worthy of serious consideration. It is obvious that the consumer of power will not consider the obligation which he owes to the community in the matter of power factor unless tariffs are devised whereby he is offered a financial inducement to install plant and apparatus for its improvement. He might rightly argue that if both a direct-current and an alternating-current supply were available he would choose the former, in which case the question of power factor would not apply. It has often been said by consumers (with some degree of reason) that as long as a supplier of electricity takes care of the wattless component of the power in any system, the consumer is not concerned in the matter as he is invariably charged on a kWh basis.

If present consumers could be persuaded to transfer from a kilowatt to a standardized kilovolt-ampere basis of charge, the result would eventually be to the advantage of all concerned.

The argument has often been put forward that supply undertakings and consumers are concerned chiefly with power factor at the time of maximum demand. This is to a certain extent true, but the fact remains that there are many undertakings with a low average power factor which could be raised and thus bring increased efficiency to both supplier and consumer.

In the drawing up of tariffs on a fair and equitable basis, it appears that in all business concerns no strictly scientific treatment is possible, but the aim generally should be to combine justice with expediency. One cannot fail to observe the difference between the methods adopted by municipal authorities and companies. The former invariably attempt to draw up and put into practice a tariff in which the selling price per unit to each consumer is based on the actual cost to the department in providing the specific consumer's supply.

In the administration of a company's affairs it is the financial result of each year's working which appeals to the shareholders, and any business which adds to the all-round financial success of an undertaking is deemed to be good, irrespective of whether any particular consumer does or does not by himself pay his proportion of the capital and running costs entailed in the provision of his supply. If a company is benefited by a combination of the whole of the consumers the net result may be considered satisfactory, even if certain consumers only pay works costs on available plant on which other consumers pay the whole of the standing charges; for this eventually decreases the cost of supply generally by improving the load and diversity factors.

The argument that power factor is only troublesome at times of maximum load is similar to the one which declares that a consumer should not pay any proportion of capital charges if his supply does not increase the maximum load on a station. This line of argument is unsound only as far as it becomes impracticable in the same manner as the "utility" of the service rendered, together with the cost of rendering that service, should theoretically result in a "market price" for the commodity. To the academic mind it appears that all steam-raising plant, and the prime-mover and coal and ash plant, etc., are unaffected by power factor and that the kilowatt output is therefore the only consideration.

This theoretical conclusion is not substantiated in practical working, for it is well known in many stations that when the power factor on the entire system falls below a certain limit it is necessary to run an additional generator with its auxiliaries, as all sets doing remunerative work are probably being then run at their maximum output in amperes. This fact affects capital charges, and also running costs, and should not be ignored.

As the raising of the power factor to unity is not a commercial proposition in any large undertaking, it might be of interest to study the result if a change from 0·8 to 0·9 could be attained. To give an output of 1 000 kW at 0·8 power factor the generator or transformer supplying the power has actually to develop 1 250 kVA, with a wattless component of 750 kVA.

By raising the power factor from 0·8 to 0·9 only 1 120 kVA capacity is required, and the wattless component is reduced to 490 kVA.

It will, therefore, readily be seen that it takes far less wattless kVA to improve a power factor from 0·8 to 0·9 than to improve it from 0·9 to unity, and it takes nearly four times as great a wattless component to change the power factor from 0·8 to unity as would be required to change it from 0·8 to 0·9.

The expressions "wattless current" and "extra current" are still used, and it is felt that these redundant conceptions could be dispensed with. The effect of an alternating current at its source and when split up by passing from one circuit to another and modifying the phase angle may be compared with an electrostatic field in a stationary condition and also when in motion as an electromagnetic wireless wave. In the latter condition the wave or field of force does not consist of the radiation of electric and magnetic energy, for the magnetic field is only cognized by the observer or the detector in the path of the impulse. In other words, it is not self-existing but is a function of the electric field and only manifests itself when its velocity or kinetic energy is absorbed or detected by a receptive apparatus. An electromagnetic wave may therefore be said to have two components, one a latent potentiality and the other kinetic, the former only coming into existence when the wave passes over or through a detector designed to be affected by the latent or magnetic component of such field. In like manner, if an alternating current be split up into two components by machines or apparatus containing magnetic circuits, one in phase with the E.M.F. and the other 90° out of phase, this latter is the idle or wattless component of the current. It is not a self-existing or separate entity and should not be called "extra current" or "wattless current." "Wattless component" is believed to be the correct expression whether of E.M.F., current or power, although the term "reactive current" is applicable, especially where the current lags behind the voltage.

The disadvantage of all a.c. machinery compared with d.c. machinery, whether generators, motors or transformers, lies in the fact that their magnetic circuits draw from the supply system current which lags behind the supply voltage, and which in effect may be regarded as being in quadrature or at right angles to the pressure. The higher the frequency of the supply the greater becomes the wattless component of the power necessary to produce the alternating field, because the charging current and the inductive voltage are proportional to the frequency. Low frequency is therefore used on phase advancers.

Electrical circuits, including transmission lines, contain inductance and capacity, and therefore are all capable of storing electromagnetic energy in the magnetic field due to the current, and electrostatic energy due to the voltage.

It should be appreciated that power factor indicates the amount of stored electromagnetic energy in a circuit and also in the medium enclosing such circuit.

With a low power factor the duty of switches, especially where placed near generating sets, is much more onerous, owing to the greater dissipation of stored energy at the moment of break. Whenever a change takes place in the electromagnetic and electrostatic conditions of a circuit—say by a fault to earth or other discharge—the voltage and current waves oscillate or travel backwards and forwards until the stored energy is dissipated, usually in the form of heat. Owing to this dissipation of energy, circuit breakers are therefore called upon to withstand much less severe duty when connected some distance from generating sets, and their duty is at a minimum value with unity power factor, where the absence of self-induction minimizes the intensity of the spark at the switch contacts.

If we consider that temperature is the factor which usually determines the maximum output of a generator, we must realize that the effect of a low power factor or lagging current is to demagnetize the field, thus demanding a bigger output from the exciter, overheating the windings generally and limiting the useful output of the set. Armature reaction and self-induction function in the same manner, for the voltage is lowered with a lagging power factor, and raised by a leading power factor.

Now that it is agreed that the transmission of large amounts of energy between interconnected power stations is a convenient and economical way of operating, it is desirable that power systems should be operated at constant pressure, and that where large amounts of energy are transmitted the respective station busbar pressures should not be varied to any appreciable extent. The proper ratio of reactance to resistance should be considered, so that the reactive drop will overcome the resistance drop in the interconnecting feeders, and thereby maintain the receiving stations at a correct pressure independent of the load transferred. Power factor seriously complicates the problem and, with loads of very poor power factor, reactors increase this and also tend to interfere with good regulation. Where a receiving station has to reduce its pressure and step back in phase, the result of this phase displacement and consequent cross current is detrimental to the efficient use of the generators, and it appears that boosters in most cases are necessary to vary the pressure on the interconnectors and supply mains, as required for loading conditions.

It may be assumed that at the point of generation the power factor is unity. Any improvement, therefore, in the direction of raising the power factor over an entire system should be effected at the points where it is reduced, viz. at the end of transmission lines and at or near the consumer's load. It is obviously wrong to install power-factor-improving plant at a generating station, as cables must still transmit heavier currents from low power factors.

Transformers do not take a large wattless component, as the magnetomotive force required to produce the necessary flux is comparatively small.

Induction motors are the principal offenders in causing a low power factor, that of the average motor varying from 0·7 to 0·85, dependent upon its size, speed and load. It is often found that a low power factor results from the installation of motors of larger capacity than is necessary for the maximum requirements, and also from the running of induction motors on certain work which necessarily involves intermittent loading conditions, e.g. presses and rolling mills, etc. It is far better to work a motor on light load occasionally than to work it on full load occasionally, although the latter is done in many cases.

### Tariffs on a kVA Basis.

Although restrictions are invariably imposed by a supply undertaking as to the limit of lagging power factor on a motor, as this varies with the load it is almost impossible on a large system to check individual working conditions; hence the resultant power factor of all connected apparatus is the criterion of the efficiency of an undertaking.

In order to correct low power factor it is necessary to educate consumers as to its undesirable properties, and also to frame and present a tariff which makes it advantageous for a consumer to correct this on his premises at or near his motor terminals. It is suggested that advice should be rendered gratuitously by a supply department to new power consumers, and that where synchronous or other plant is installed which draws current at unity or leading power factor, a rebate should be allowed on each monthly or quarterly account.

Where special machines or apparatus have to be installed, whether by suppliers or consumers, it is essential to show that the annual saving will justify the initial expenditure and also the running costs—including depreciation—on this power-factor-correcting plant. From the supplier's standpoint the saving of capital expenditure at the power station and distributing system, together with the increased operating efficiency and better voltage regulation, must be considered, and a valuation made so as to determine whether the savings effected by raising the power factor from, say, 0·75 to 0·9 on the entire system will compensate for the cost of rectifying the low lagging component.

It is obvious that where a consumer pays on a kVA basis and subsequently installs rectifying plant to improve his power factor, his cost of energy is reduced and the result is an immediate loss in revenue to the supply department. It should be borne in mind, however, that the supply and distribution plant has at once a greater potential value, and additional consumers can be connected without increasing the capital charges, which often amount to double the works costs per unit sold.

To penalize all consumers by increasing the flat-rate cost of power to pay for the rectification of a low power factor on any system would obviously be inequitable. In the interlocking mechanism of industry, the happiest and most successful results can only be attained by a system mutually advantageous to both buyer and seller. A reciprocal price list should be framed which will ensure the maintenance of a reasonable power factor to the supply authority and a concession to the consumer whenever he provides a better power factor than is declared at the outset. Alternators and transformers are purchased on a kVA basis, hence it is reasonable to suggest that each consumer should pay the capital charges and running costs of the plant required for his supply on a kVA basis, with a concession where such supply is not required during the hours of peak load. Very little useful purpose is served if power factor conditions and regulation clauses are drawn up in such a manner that they cannot be enforced.

On an a.c. system the simple unit charge cannot be scientific in principle or equitable in its general application. An important and altogether desirable step towards an increase of efficiency has been made by the Electricity Commissioners in the Electricity (Supply) Act 1922, in repealing the section of the Electric Lighting Act of 1899 which embodied a compulsory flat rate per unit chargeable at the option of any consumer.

Now that a supply authority may charge on either a kVA or kW basis it appears that a simple and equitable arrangement would be to base the tariff on the average kVA demand for a period of 20 to 30 minutes, in order to provide for capital charges, plus a charge per unit to cover the operating costs, with a sliding scale or basis of charge below or above the agreed standard power factor. This sliding scale would operate in a similar manner to the usual coal-price clause in many existing agreements, although it is unfortunate that consumers could not so easily control and check their accounts, owing to the more complicated arrangements for metering.

It is felt that all consumers should appreciate the fact that no undertaking is desirous of selling a commodity which is useless, and that wattless energy is a bugbear to both seller and buyer. Even to call it "energy" is to flatter it. Instruments must therefore be connected at consumers' premises which will differentiate between the active energy and the useless energy which is brought into being by the voltage consumed by self-induction or alternation of the magnetism of a.c. machinery.

### METERS AND MEASUREMENTS.

It should not be deemed necessary for a consumer to have a knowledge of trigonometry and to realize that the reading of a sine meter divided by the reading of a cosine meter gives the tangent of the angle of lag, and that power factor is the numerical equivalent to the cosine of the angle of current lag; in other words, the ratio of the total watts to the vector sum of the volt-amperes in the several phases. It is sufficient for a consumer to know that the power factor of a circuit is the ratio of the real effective watts to the apparent watts; and the former are the only ones worth paying for.

It appears that to arrive at a consumer's general working conditions often involves averaging one or more of the required factors. This is fairer than to take maximum records which may not be sustained for more than a few minutes and should therefore have no appreciable effect on any part of a supplier's system. The question of using an integrating ampere-hour meter for kVA-hour measurements has received consideration, but such an instrument has not yet been perfected and used to any considerable extent on a.c. circuits. There is a difficulty in compensating for voltage fluctuations, and no circuit can be deemed to be of constant pressure. A simple instrument is still required to integrate and record direct the average kVA during any time, as distinguished from the momentary value. Wattless-component meters are on the market which record the wattless-component consumption (kVA-hours multiplied by sin $\phi$). These meters are generally connected in series with watt-hour meters, and if the reading of the wattless-component meter be divided by the reading of the watt-hour meter the tangent of the mean angle of lag is obtained and the phase displacement determined. For unbalanced loads and fluctuations of power factor, accuracy is not obtained, but for all practical purposes this is not vitiated to any unreasonable extent. Where a leading wattless component exists such meters may be fitted with stopping devices to prevent them from running in a reverse direction.

It is not desirable, as a general rule, for power-factor-correcting devices—such as static condensers—to be kept in circuit continuously, thereby cancelling during the night-time some, or the whole of the kVA registered by the meter on the lagging side during usual working hours.

There appears to be no standardized system of charging for high- or low-tension electrical energy on a kVA basis at the present time, and each authority has its own particular tariff, neither is there any standard method of arriving at the power factor of individual consumers' loads. It is generally agreed that a recording power-factor meter and a wattless-component meter, together with a maximum-demand indicator of the thermal type and a kWh meter, form too expensive a combination for small consumers. If a polyphase system is balanced, viz. if it carries the same load at the same power factor, the total power can be calculated by multiplying the power delivered to one phase by the number of phases. In practice this balance is seldom maintained, hence it is usual on both two-phase and three-phase systems to measure the power by means of two wattmeters. If the power factor is greater than 0·5, which means that the angle of lag is less than 60°, both meters give positive readings and their sum is the total power. In many industrial cases the power factor is less than 0·5, in which case one meter will read positive and the other negative, and the difference of the two readings is the total power. If the angle of lag is 90° both meters register the same, but, as one is plus and the other minus, the current is idle and the total power is zero. At unity power factor each meter reads the same, and the sum is the total consumption. In three-phase measurements it is quite common to have a phase difference of more than 90° between the currents in the pressure and series coils of a meter, thus causing a reversal of the wattmeter reading. Where the neutral is accessible, three wattmeters may be used so that the power delivered is measured on each phase separately and independently, and the total power is the sum of the three meter readings. It is suggested that the energy in kW and kVA should be separately allocated and invoiced so that a consumer may check and understand the state of his installation, and if possible improve his power factor and thereby obtain a rebate. Regardless of the number of meters required, no rental should be charged to power consumers.

For simplicity it is recommended that for two-phase and three-phase circuits two integrating watt-hour meters of the ordinary construction should be used, and the monthly power factor ascertained by the ratio of the units registered by these two meters.

*Example.*—Wattmeter reading $R_1 = 20$ kWh.
Wattmeter reading $R_2 = 10$ kWh.

$$\tan\phi = \frac{(\sqrt{3})\,(20 - 10)}{20 + 10} = 0{\cdot}577$$

This corresponds to an angle of 30°. Since cos 30° = 0·866, this will be the power factor.

It is felt that the maximum demand in kVA with a reasonable time-lag should also be determined monthly, for if this is taken over a period of, say, 12 months, it is often found that consumers refrain from using motors, etc., at certain times, so as to keep the maximum demand at the lowest figure. This is disadvantageous to a supply department, and a clause has had to be inserted in some agreements specifying that if the total price under a kVA charge proves higher than under the flat-rate kWh charge, the accounts will be invoiced at the lower rate. Where the average power factor over, say, one month has been obtained, it is suggested that the basis charge per kVA of demand should vary wherever the declared or standard power factor is improved or reduced.

Ignoring the usual coal clause (which, incidentally, can neither be scientific nor equitable without a standard calorific value) the ultimate price would be :

The basic price at standard power factor (say £4 per kVA) $\times \dfrac{\text{standard power factor (say } 0{\cdot}8)}{\text{average power factor}}$.

*Example.*—Average monthly power factor = 0·7 lagging ; 0·8/0·7 = 1·14, i.e. the multiplying coefficient which raises the price to £4·568 per kVA. If the supply were taken at unity power factor then £4 × 0·8/unity = £3·2 per kVA. It is further suggested that a rebate of 1 per cent on the maximum-demand charge should be allowed for each 1 per cent improvement beyond unity, for this improves the entire undertaking, especially the generators, as the work on the rotors is thereby reduced. Fig. 2 shows curves of costs on this basis.

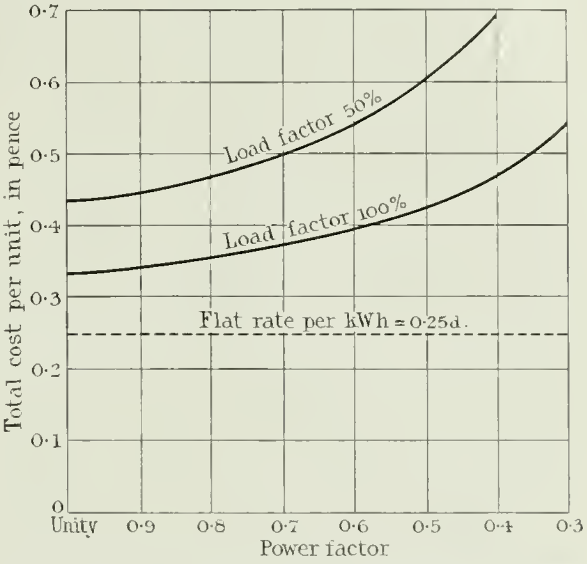


FIG. 2.—Curve of total costs per unit, based on £4 per kVA × (standard power factor, say 0·8 )/(average power factor) + 0·25d. per kWh.

### DEVICES FOR CORRECTING LOW POWER FACTOR.

There are several ways and means of effecting an improvement of power factor, and each should be considered on its merits for each individual case from a technical and commercial standpoint before a decision is made. It is regrettable that in the present advanced state of electrical engineering there is no device on the market which, while simple, cheap and effective, can be connected to small induction motors. It is not beyond the realm of probability that some device will be forthcoming, in addition to the static condenser, which will not require the introduction of a commutator or an extraneous direct-current supply. Exciters are commercially unsuitable for motors under, say, 60 h.p. Two devices are usually employed for power factor correction on large motors, one of which affects the characteristics of the motor and the other does not. The first is known as a phase advancer of the rotating or vibrating type. Its function is to supply the magnetizing current of the motor to the rotor, so that magnetizing current is not drawn from the mains. With a motor excited in this manner a smaller current flows in the stator windings, with the result that there is a slight increase of efficiency on the motor, so that from a design standpoint a smaller frame might be used for the same output. An increase in the falling-out-of-step margin is also effected. Phase advancers are only suitable for large slip-ring type motors and their action is to increase the slip, although the Walker phase advancer may be designed to reduce the slip slightly. The second device is the static condenser. This does not supply the magnetizing current to the motor, and therefore the efficiency of the motor itself is not increased. It has been stated that static condensers cause resonance, but this has not been proved to be a serious matter. Every apparatus on the market may be said to have a definite field of usefulness, and whether it is more advantageous to install stationary or moving machinery to effect the desired result can only be determined after all the factors are considered. It is obvious that if a machine instead of running idle can be used on remunerative work and at the same time improve the power factor of an installation, the application of such machine should be considered. Where direct current is required from an a.c. supply the rotary converter or motor converter has many advantages over a motor-generator. These machines draw current at unity power factor and, if desired, at a low, leading power factor, which will compensate for a low, lagging power factor on any system. If no concession is given to a consumer it is obvious that he will not pay for a higher kVA-rated machine which might be necessary to supply a leading wattless component, or to install synchronous induction motors or single-phase commutator motors at a higher cost in place of the ordinary type.

As a rotary converter is essentially a power-factor-correcting machine, a great improvement in efficiency is attained on any a.c. system where such machines are connected. An average power factor of about 0·93 is obtained on some company and municipal undertakings where a large d.c. load is supplied through rotary converters.

Where there are long overhead transmission lines rotary synchronous condensers have been largely used for correcting power factor and maintaining the required voltage regulation. Many thousands of pounds per annum have been saved by installing these machines, which are capable of being used, if required, as over-excited motors instead of running light, in which case a comparatively small increase in their kVA rating will enable them to perform continuous work. Idle-running machines are not often used by consumers, as the energy losses compare very unfavourably with those of phase advancers or static condensers.

## APPENDIX.

TOTAL COSTS PER UNIT AT 50 PER CENT LOAD FACTOR WITH VARIOUS POWER FACTORS BASED ON £4 PER ANNUM PER KVA OF DEMAND AT 0·8 POWER FACTOR, PLUS 0·25D. PER KWH.

(Curves shown in Fig. 2.)

| Power factor | Cost per kVA per annum | Cost per kVA per kWh | Cost per kWh | Total cost |
|---|---|---|---|---|
| | £ | d. | d. | d. |
| Unity | 3·2 | 0·1752 | 0·25 | 0·4252 |
| 0·9 | 3·6 | 0·1972 | 0·25 | 0·4472 |
| 0·8 | 4 | 0·2190 | 0·25 | 0·4690 |
| 0·7 | 4·57 | 0·2504 | 0·25 | 0·5004 |
| 0·6 | 5·333 | 0·2922 | 0·25 | 0·5422 |
| 0·5 | 6·4 | 0·3506 | 0·25 | 0·6006 |
| 0·4 | 8 | 0·4382 | 0·25 | 0·6882 |
| 0·3 | 10·666 | 0·5844 | 0·25 | 0·8344 |

COMPARISON BETWEEN STATIC AND ROTARY SYNCHRONOUS CONDENSERS.

| | Static condenser | Rotary synchronous condenser |
|---|---|---|
| Capacity of condenser . . | 1 500 kVA | 1 500 kVA |
| Total cost . . . . | £6 500 | £3 700 |
| Cost per kVA . . . . | £4·37 | £2·44 |
| Kilowatt loss (light) . . | 0 | 55 |
| Kilowatt loss (loaded) . . | 7·5 | 75 |
| Yearly energy losses (light) | 0 | 348 000 units |
| Yearly energy losses (loaded) | 47 500 units | 475 000 units |
| Necessary correction in total kVA before a profit can be obtained | 75 | 760 |

TYPICAL EXAMPLES OF THE APPLICATION OF POWER-FACTOR-CORRECTING DEVICES.

*Static Condensers.*

| Installation | Capacity of condensers | Average power factor of works (pre-condenser conditions) | Average power factor of works (post-condenser conditions) | Total cost of condensers |
|---|---|---|---|---|
| 923-kVA rolling mill, 3 000 volts | μF<br>326<br>(in 3 units) | 0·545<br>Max. demand, peak kVA = 4 020 | 0·73 under similar working conditions<br>Max. demand, peak kVA= 3 373·5 | £4·37 per kVA (inclusive of switchgear) |
| 576-kVA general a.c. services, 440 volts | 9 470<br>(in 5 units) | | | |

With this installation the total cost of these condensers will be paid for within three years by the savings in kVA under the maximum-demand system of payment.

*Kapp Oscillatory Phase Advancers.*

| Installation | Current in rotor | Original power factor | Improved power factor | Total cost |
|---|---|---|---|---|
| 300-h.p. motor, three-phase, 40 periods, 2 750 volts | amps.<br>235 (without advancer)<br>280 (with advancer) | 0·855 at ¾ load | 0·99 at ¾ load | £290 (including switchgear) |

With this installation the saving in kVA is 51·9.

*Miles Walker Rotary Phase Advancers.*

| Installation | Capacity of phase advancer | Original power factor | Improved power factor | Total cost |
|---|---|---|---|---|
| 430-h.p. motor, two-phase, 50 periods, 6 600 volts | 12·5 kVA | 0·85 (lagging) | 0·6 to 0·9 (leading) | £600 |

## DISCUSSION BEFORE THE SHEFFIELD SUB-CENTRE, AT SHEFFIELD, 17 JANUARY, 1923.

**Mr. H. West**: The frequent articles appearing in the technical Press, and the discussions which have taken place at meetings of kindred societies both in this country and abroad as to the best method of dealing with the difficulties arising out of low power factor, are a clear indication of the importance to both supplier and consumer of the subject dealt with in the present paper. It is generally admitted that the maintenance of a high power factor acts in the interests of all concerned, and I therefore feel that both the supplier and the consumer should take steps to ensure such a condition. To be most effective, power factor improvement must be carried out at the outer end of the feeder, i.e. on the consumer's premises. There is no technical difficulty about this, and a number of devices are available for the purpose. Their capital and running costs are generally much less than the cost of a bad power factor, so that their installation is commercially sound and must eventually result in the cheapening of electricity. The difficulties of supervision and divided responsibility make it undesirable for the supply undertaking to pay directly for devices which are accessories to the consumer's plant, and so the part to be played by the supply engineer would seem to be to devise a tariff which would give every inducement to the consumer to install such devices. I agree with the author that the continuation of the present general kWh basis of charge is not desirable so far as a.c. supply is concerned, as it offers no inducement to correct the poor conditions associated with many installations to-day. To be satisfactory, the tariff must make sufficient difference between the electricity bills for good and bad power factors, respectively, to make it worth the consumer's while to effect the necessary improvement. It must be simple, and the consumer must be convinced of its fairness. It must be possible to determine with accuracy the quantities for which a charge is made, and the instruments for doing this should be reliable and inexpensive.

**Mr. W. E. Burnand**: There is no doubt that this question is steadily becoming more serious and is keeping the cost of electric supply considerably higher than it should be with good power factor. At the same time, as this subject is so intimately connected with tariffs, and as these tariffs are devised by the electric supply undertakings who now complain about that power factor, one is inclined to think that they have only themselves to blame. This is due to the supply tariffs not being based in accordance with the elements of the cost of electric supply, with the result that wattless kVA has been supplied apparently free of charge, and has in consequence been wastefully used. The cost to the suppliers of the wattless component of the current is about one-third the cost of the unity power factor current per kVA-hour, and the logical and, I believe, the correct way to tackle this problem is to charge for the kVA-hour on a basis corresponding to this. If, for instance, these wattless kVA units are sold at three for 1d., returning the same percentage of profit to the supply people as would the unity power factor current, this should be a more satisfactory basis than to supply a large number nominally free of charge and impose penalties, or more often threaten penalties which could not be imposed, for any wattless current taken beyond the nominal maximum value. It represents, indeed, the difference between a business transaction and a very unbusinesslike method, giving the maximum of friction and dissatisfaction and returning the minimum of revenue for the expenditure involved. It should also be borne in mind that these wattless units are by no means useless, as they form, in effect, the fulcrum on which the power units react in the induction motor, so that on a proper basis a consumer gets at a reasonable figure a commodity of value which he could utilize efficiently, or otherwise, according to temperament or the conditions of working, and the irritating question of penalties and the like does not arise. This system is already employed in France, in some cases two meters being used, one measuring the wattless component and the other the watt component of the current. These are charged at the corresponding rates. In another system the two meter units are in one case, the wattless component unit being geared to the indicating mechanism in the ratio of 3 to 1 as compared with the watt component. This has the advantage that only one reading is involved, but has the disadvantage that, should the ratio of cost of supply of wattless to watt component of the current alter its present-day ratio, which I think it is quite reasonable to expect will be the case in time, this gear ratio would have to be changed. The system is less elastic than that of simply altering the charge per kVA-hour for the two components in the event of any considerable alteration occurring. If the two components were charged as separate items, and were referred to as "magnetizing current" and "power current," it would convey a more correct idea of their use and action than referring to them as "wattless current" and "unity power factor." The author appears to incline towards the maximum-demand system, but in my opinion this is fundamentally wrong, and it would require much ingenuity to devise a worse system nominally based on what is undoubtedly a correct principle first brought prominently forward by Hopkinson, who showed that the cost of supply could be split into two main components, one representing the capital outlay and the other being proportional to the amount of energy taken. But Hopkinson never stated that the capital outlay or any other cost of supply varied from month to month in accordance with 20-minute indications of a device resembling the maximum-demand meter. In addition to charges under this system bearing only a slight resemblance to the cost of supply, this indicator acts as a constant check on the use of current and, by inducing to some extent a cheeseparing attitude of mind on the part of the consumer with regard to using current at anything above the minimum possible rate, will lose more revenue to the suppliers than the mouse-trap characteristics of this device will gather in. Numerous devices have from time to time been put forward for improving power factor, but nearly all these involve very considerable expense, and the gain in efficiency is so insignificant, even under favourable conditions, that I think that under average working conditions the actual efficiency of the motors utilizing these phase advancers will by their use be lowered much more often than it is raised. In addition, phase advancers usually involve considerable complication, and, in the event of anything going wrong with them, the characteristics of the machines specially made for use with these advancers to get the maximum benefit from them are such that the power factor is materially lower than that of the standard machines made for use without phase advancers. Also, nearly all these phase advancers are really series machines, which means that if the motor is run for any considerable portion of its time on no load, the power factor under these conditions is decreased below that of the machine working without the phase advancer. This will be seen in Dr. Kapp's paper * in 1913, in which are given curves of power factor with and without advancers, and it will also be seen that if the curves are continued to no load they will cross one another at the lower end. This may not, of course, apply to many cases, but as it is on no load when the power factor is lowest, it is unfortunate that there is no gain under these conditions, and a successful shunt-characteristic phase advancer has not to my knowledge been devised for use for non-synchronous machinery. With synchronous machines the case is better, but the fact that they are synchronous machines introduces serious limitations. The high cost and extra parts still remain, and it will take some very strong argument to get these into use sufficiently to have any considerable effect on the power factor of a large system until the supply undertakings charge on a business basis directly for the wattless component which costs so much to supply and is really a valuable commodity to the user. It might be thought that the cost of supplying the wattless component over a long line would be much greater than over a short distance, but, owing to the capacity current on the line, the actual cost to the supplier of the lagging wattless component, where supplied from a generating station 20 miles away, will not be greatly different on the whole from that it would be if supplied over a distance of, say, 1 mile, so that the

---

* *Journal I.E.E.*, 1913, vol. 51, p. 243.

ratio of cost of wattless to watt components of the supply would remain approximately constant over a big supply system.

**Mr. A. E. Jepson:** It appears to be absolutely necessary for some charge to be made for kVA maximum demand, in the effort to put an end to the very bad power factors experienced on the electricity supply mains and generators. My view of the matter was that the difficulty was not so much in persuading a number of engineers to adopt such a scheme, as in offering them a suitable instrument. As a matter of fact, at the present time there is no meter on the market which can be considered to be properly accurate for measuring kVA maximum demand with any prearranged time-lag. There are various substitutes employed, e.g. the printometer, the thermal demand indicator, and the specially adjusted meter arranged to read high with low power factors. All these have their drawbacks, as also have the later ones, such as the a.c. ampere-hour meter arranged with maximum-demand indicator. The printometer is certainly the most scientific, but it is impracticable on all but the largest supplies. What is actually wanted is a meter which will read correctly on all power factors and on all loads, and as there is a demand for it there is no doubt that sooner or later it will be produced. The main advantage in the kVA charge would be that, due to the penalty imposed for a bad power factor, consumers would voluntarily install a power-factor-improving device, such as Kapp phase advancers, synchronous motors, condensers, etc., and thereby enable the mains and plant to give greater output. We have some Kapp phase advancers working very successfully at local collieries, and in some cases they have enabled an extra turbine to be shut down. The difficulty of measuring the maximum kVA in a large works having three or four supplies has easily been overcome in many cases by carrying leads from the secondaries of current transformers, having a fairly high volt-ampere capacity, and summing all the readings in one meter. It has been done not only for two a.c. supplies, but for two or three a.c. supplies and two d.c. supplies, on a kW maximum-demand basis, although this method is not generally necessary, as the d.c. and a.c. supplies should be dealt with on a separate basis.

**Mr. S. James:** Fig. 2 shows very clearly how the cost of supplying electrical energy increases as the power factor decreases. It is obviously unfair to ignore the effect of power factor and to charge all consumers at the same rate, since this involves supplying the low-power-factor consumer possibly at a loss, which is made up by overcharging the consumer who has a good power factor. A number of undertakings in this country do actually vary their price for electrical energy according to the power factor of the load, but the method of determining the power factor is frequently unsatisfactory. The author gives an example of the calculation involved in this determination and it will be observed that after the meter readings have been taken it is necessary to refer to tables of cosines and tangents or to suitable charts from which the readings can be correlated. The objections to this method are several. The average power user does not understand this method of determining power factor and is likely to view the proceedings with a certain amount of suspicion. The services of some technical person are required to make the calculation which, incidentally, is accurate only provided the load is balanced. If condensers are installed for the purpose of improving the power factor, it is possible, by leaving them connected for 24 hours per day, to improve the average until it approaches, or actually reaches, unity, while at the same time the power factor at the time of peak load may be very bad. Thus the object of a tariff based on the average power factor would be entirely defeated. With a view to removing these objections a meter giving a direct indication of the average power factor and eliminating all calculations has recently been placed on the market by Messrs Chamberlain and Hookham. It is thus possible for the consumer to see at a glance the minimum value of his average power factor over a period and to take steps to effect improvement. The meter reader can reset the indicator to zero after taking the monthly reading. The method of making this measurement is very simple. An energy meter is connected in series with a wattless component meter fitted with a maximum-demand indicator. In place of the clock used in connection with a maximum-demand indicator, a contact-making device is fitted on the energy meter and arranged to close a pair of contacts periodically, after the passage of a fixed amount of useful energy. The closing of these contacts effects the resetting of the demand indicator on the wattless component meter in the usual manner. The scale of this indicator is graduated in terms of power factor instead of maximum demand in wattless kVA. Referring now to Fig. 1, the principle of this combination will be made clear. Along the base of the graph is plotted energy load in kW, and up the left-hand side is plotted the wattless kVA. We may substitute for these quantities energy in kWh and wattless component in kVA-hours without affecting the other quantity plotted on the right. Now assuming that this graph represents the readings of the two meters referred to and that the contact maker on the energy meter is set to operate each time 1 000 kWh has been used, it will be seen that, if both meters start from zero at the same time, the readings on the indicator at the end of the first period between two successive contacts will be a measure of the number of wattless kVA-hours used during the interval represented by the passage of 1 000 kWh of energy. But a definite ratio exists between the number of kVA-hours used and the average power factor during this interval, and it is thus an easy matter to mark the scale of the indicator in terms of power factor instead of wattless kVA-hours. In a series of intervals, the indicator will give the minimum power factor equivalent to the maximum wattless kVA-hours occurring in any one of the intervals. The period between successive contacts can be varied over wide limits to suit varying circumstances. It may be equivalent to the consumer's normal load for 1 hour, 1 day, 1 week or for any other period, and I think that two or three times per day would probably be satisfactory in the majority of cases. In practice it sometimes happens that a consumer has a small load at a low power factor during the night and at week-ends, and it may be urged that he should not be penalized on this account. Fortunately, the use of this instrument does not involve any such penalty, because the time required to give an indication varies inversely as the power factor and the load. For example, an instrument arranged to make contact every two hours when the consumer has full load at unity power factor, would require eight hours to give its maximum reading if the value of the current remained the same and the power factor fell to 0·25. Further, if the current was reduced to one-tenth of its previous value and the power factor remained at 0·25, 80 hours would be necessary to obtain the reading. Therefore, unless a small load at a low power factor is maintained for an unreasonable time, there is no fear of penalizing a consumer for an occasional small load at low power factor. On the other hand, if it is desired to make the consumer pay for these periods of low power factor and small load, it is possible to do so by considerably reducing the time elapsing between successive contacts, and, to go to the other extreme, it is possible to measure a consumer's average power factor instead of his minimum average over a month by simply extending the contact period so that it occurs only once or twice during this time. Furthermore, the power factor may be measured at the time of peak load only, if desired, by inserting a time switch which cuts out the indicator at other times. It will thus be seen that this instrument is most adaptable and makes possible the use of tariffs based on power factor which have hitherto been impracticable in most cases. This method of measurement also gives accurate readings on unbalanced loads, whereas the usual method, as explained on page 679, is accurate only on balanced loads. At the foot of page 678 the author states that a simple and equitable charge for electrical energy would be to base the tariff on the average kVA demand for a period of 20 to 30 minutes. There is much to be said in favour of a kVA demand charge, but, on the other hand, it is not entirely free from disadvantages. If the demand is measured at the time of peak load it is not objectionable, but supply undertakings would, I think, in the majority of cases welcome additions to the load during off-peak hours. The effect of a kVA demand charge is to tend to limit the consumption of electrical energy during off-peak hours, unless such demand is measured only at the time of peak load. The author truly states that a simple instrument is still required to integrate the average kVA during any time, as distinguished from the momentary value. Many attempts have been made within recent years to devise a kVA demand indicator, but the problem is very difficult. Such instruments as have been used or proposed are either inaccurate or too costly. Several types of demand indicators have been used, the indications of which are dependent on the current in the circuit and which ignore the voltage. Such instruments may be very unfair to the consumer in cases where the voltage fluctuates or the load is unbalanced. For example, take the case of a consumer whose maximum current is 100 amperes at normal voltage. It the voltage falls to 10 per cent below normal and the consumer's kVA demand remains the same, the current will increase to 111 amperes.[*] The demand charge would thus be increased by 11 per cent, although the actual kVA demand was unaltered. If a single-phase instrument is used on a three-phase unbalanced load, considerable discrepancies may arise in the charge for energy. It is very rare that the load is perfectly balanced and, if the indicator is on the phase with the heaviest load, the consumer will be overcharged. If the demand charge is a large proportion of the total, a small error in arriving at the maximum demand may involve a considerable sum in the account, either for or against the supply authority. Another type of kVA demand indicator is also made which takes into consideration the variation in voltage, but this is accurate over only a small range of power factor. Such an instrument can be made accurate at some particular power factor, and, provided that the angle of lag at the time of maximum demand does not depart more than 14° from the angle at which the instrument is calibrated, the error will not exceed plus or minus 3 per cent, in addition to the ordinary meter error. An instrument correct at 0·8 power factor would have errors up to plus or minus 3 per cent on power factors between 0·92 and 0·63. Outside these limits the errors increase very rapidly.

**Dr. T. F. Wall**: The section of the paper in which I am especially interested is that in which the means for improving the power factor are considered. I refer more particularly to the paragraph in which the need is expressed for some practical and economical method of phase advancing for small motors. Since the date on which this paper was first communicated to the Institution, I have given at a meeting of the North Midland Centre some details of tests with a new type of phase advancer which is specially adapted for use with small and medium-sized motors, say from about 10 h.p. to 100 h.p. Briefly stated, the device comprises one or more cells connected in each phase of the rotor circuit. Each cell has two electrodes immersed in sulphuric acid, the electrodes being identical in every way and consisting preferably of grids pasted with an oxide of lead such as is used in manufacturing the plates of a lead accumulator. When an alternating current is passed through such a cell, it acts like an accumulator on charge and stores electricity during one part of the cycle, and during the other part of the cycle the stored electricity is released and the cell becomes charged in the opposite direction. In other words, each cell behaves to an alternating current like a condenser of very large capacity. Each such cell is capable of giving a capacity reactance voltage of about 2 volts, and forms, as the subsequent example shows, a very suitable means for phase-advancing by connecting such cells in the rotor circuit of an induction motor. That such a cell actually does produce a leading current and therefore acts like a condenser is shown by the oscillogram in Fig. A. I have found it useful in dealing with practical phase-advancing problems to use a simple formula by means of which the necessary injected volt-amperes to produce a given alteration in the power-factor at a given load may at once be determined, whether the desired phase alteration is produced by injecting the volt-amperes into the stator circuit or into the rotor circuit. Referring to Fig. B, which is a vector diagram for one stator phase, if it is desired to improve the power factor from $\cos\phi$ to $\cos\phi_1$ the current must be reduced from OC to OB. In order to effect this alteration of the stator current the wattless component, BC, per phase may be injected into the stator winding. The total wattless volt-amperes to be injected in the stator winding to produce the required improvement in the power factor is

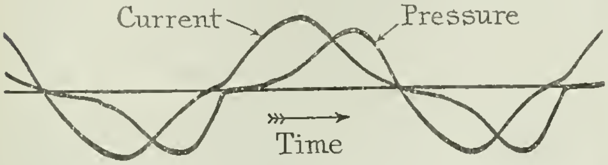


Fig. A.—Grids pasted with an oxide of lead and immersed in dilute sulphuric acid; supply frequency 2·45 periods per second.

$$\begin{aligned} mV(\mathrm{CB}) &= mV(\mathrm{AC} - \mathrm{AB}) \\ &= mV(I\sin\phi - I\cos\phi\tan\phi_1) \\ &= mVI(\sin\phi - \cos\phi\tan\phi_1) \text{ volt-amperes} \end{aligned}$$

where $m$ is the number of stator phases.

The same effect is produced if there is injected in the rotor circuit

$$smVI(\sin\phi - \cos\phi\tan\phi_1) \text{ volt-amperes}$$

where $s$ is the rotor slip. The above formulæ give results which are correct to a very close approximation.

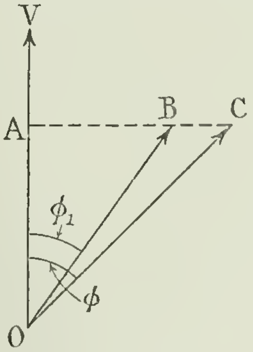


Fig. B.

The enormous practical advantage obtained when phase-advancing is produced by injecting a leading component of pressure into the rotor circuit instead of into the stator circuit is evident.

*Example.*—Suppose it is required to improve the power factor of a 20 h.p. motor from 0·85 to 0·95. We have

$$\cos\phi = 0{\cdot}85\,; \quad \cos\phi_1 = 0{\cdot}95$$

Assuming the efficiency of the motor to be 88 per cent, then

$$mVI\cos\phi = \frac{20 \times 746}{0{\cdot}88} = 17\,000$$

or

$$\begin{aligned} mVI &= 20\,000 \text{ volt-amperes} \\ &= 20 \text{ kVA} \end{aligned}$$

If the power factor is to be improved by connecting static condensers across the stator terminals, the condensers must be capable of dealing with

$$\begin{aligned} &20(\sin\phi - \cos\phi\tan\phi_1) \text{ kVA} \\ &= 20(0{\cdot}527 - 0{\cdot}85 \times 0{\cdot}33) \text{ kVA} \\ &= 4{\cdot}94 \text{ kVA} \end{aligned}$$

If, however, the power factor is to be improved by connecting a phase advancer in the rotor circuit, the phase advancer need only be capable of dealing with

$$s \times 4{\cdot}94 \text{ kVA}$$

where $s$ is the rotor slip.

If, for example, the slip is 3 per cent, i.e. $s = 0{\cdot}03$, it is only necessary for the phase advancer to inject $0{\cdot}03 \times 4{\cdot}94$ kVA $= 0{\cdot}148$ kVA, to obtain the requisite improvement of power factor. If the rotor current is 40 amperes per phase, then the phase advancer has to inject only $v$ capacity reactance volts per phase, where

$$3 \times v \times 40 = 148 \text{ volt-amperes}$$

or

$$v = 1{\cdot}24 \text{ volts}$$

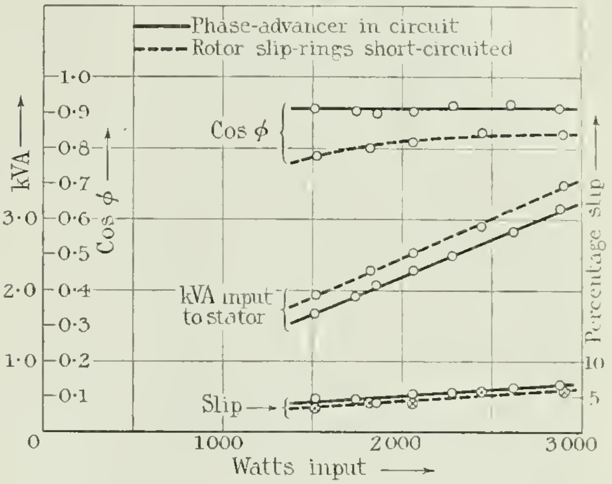


Fig. C.

It is therefore apparent that the correct method of improving the power factor of slip-ring induction motors is to inject the capacity reactance volts in the rotor circuit and not in the stator circuit. An electrochemical phase advancer of the type described has been in operation in a factory in Sheffield for some time and is working in a very satisfactory manner. In order to obtain some data as to the life that this phase advancer may be expected to have, arrangements were made to put one into operation in connection with a 4 b.h.p. motor in daily service in the Suffolk-road factory of the Sheffield Corporation Electric Supply Department, and Fig. C gives the test data taken after the phase advancer had been in operation for 3 weeks. This apparatus is being left in circuit with the motor, and tests will be made at intervals to ascertain what its life will be.

**Mr. G. H. Fletcher:** There is a threefold aspect of the low-power-factor problem, as follows: (1) The avoidance of low power factor by a judicious choice of apparatus; (2) the adoption of special apparatus, the sole purpose of which is to improve the power factor; and (3) the correct method of charging consumers who draw a large wattless component from supply. I intend to confine my remarks to the question of the avoidance of low power factor, and I think it will be readily agreed that the chief difficulty in this connection is the induction motor and, in general, the small industrial motors of this type. The main factors in the design of an induction motor which have a bearing on the power factor are (1) Maximum pull-out torque at full load; (2) speed; (3) type of rotor (squirrel-cage or slip-ring); and (4) output margin. Where users install a motor with a very much larger pull-out torque than is required, the effect is to reduce considerably the power factor at a normal working load. For instance, a motor designed for a maximum pull-out torque of 100 instead of 150 per cent overload may give improvements of power factor of from 4 to 5 per cent. The speed of an induction motor has, of course, very considerable bearing on its power factor, although it is realized that in many cases where direct drive is adopted the speed of the motor is outside the control of the engineer installing the motor. Where, however, an indirect drive can be adopted it is advisable to adopt the highest practicable speed. The slip-ring motor has a very much higher leakage coefficient than the squirrel-cage motor, and consequently gives a lower power factor. In my opinion the squirrel-cage motor could be used much more frequently than at present, especially for small sizes. I believe that in many cases there is a much bigger margin between the normal output of a motor and the actual load at which the motor operates, and many cases have come to my notice where the normal output of a motor is two or three times the service requirements. If a margin is desired it will be preferable to have this in temperature-rise rather than in output. For instance, if the service requirements in a given case are estimated at 50 h.p., and a margin of 10 per cent is required, it would be better from the point of view of power factor improvement to specify a lower temperature-rise for the estimated horse-power, rather than increase the nominal rating of motor in horse-power.

**Mr. A. R. Chaytor:** Speaking as a consumer who has given close attention to the subject of power factor and its effect on the electricity account, the subject appears to me in a somewhat different aspect from the opinions expressed by most of the previous speakers. Whilst I do not disagree with the method of charge being based on a kVA maximum-demand charge plus a kWh charge, I agree with the author that the ideal type of maximum-demand meter and system of charging has not been evolved, and it certainly is time that something tangible was done by the supply authorities to agree upon a basis as to a reasonable average power factor. Some undertakings stipulate 70 per cent as a reasonable working basis for the consumers' average power factor, and others stipulate 85 per cent. Furthermore, there appears to be as much variation in the average power factor basis on which a penalty or rebate is brought into effect in the different undertakings, whilst the amount of the penalty or rebate varies to a still greater degree. From the consumers' point of view, low power factor is at times practically unavoidable, and will be so long as group drives and intermittent variable loads are requisite, as any engineer who has had to run a works during variable trade conditions will have discovered, particularly if his method of charging is based on kVA of maximum demand. The trouble of low power factor in the former case can be overcome, where it lasts for an extended period, by changing the motor for one of lower horse-power, but the difficulty of different dimensions of motor and cost of changing (assuming that the smaller spare motor is available) has also to be considered. In a large number of cases it has been found more economical to leave the original motors in position and to run them with the stator windings connected in "star" as the running position (instead of in "delta") during periods when some of the machines were idle and when the motor would be working to only half its normal rating, with improvement to both efficiency and power factor. Conditions which affect the consumer's account, but which arise from excessive variation in either pressure or frequency, or both, are seldom, if ever, mentioned in technical discussion, but my experience leads me to the conclusion that an excessive pressure-drop for a period of 10 to 15 minutes during a period of normal load has been responsible for the registered maximum demand on which the account was based. Recently a case occurred in which the frequency was 6 per cent low for a period of about 20 minutes, and although the load was restricted and power factor improvement by rotary condenser tried to the full extent, the result was a higher maximum demand than could reasonably be considered equitable to base the account on. It therefore behoves large consumers who are considering new agreements, particularly where the maximum demand is registered as kVA, to see that no wider variation of either pressure or frequency is permitted to the supply authority than those considered reasonable in the B.O.T. Regulations, otherwise even a short period of excessively low frequency or low pressure may result in an increased account due to the higher kVA maximum demand registered. From the foregoing it would appear that there is some justification for the strong objections which have been expressed by previous speakers to the maximum demand being based on kVA, but with normal conditions of supply existing even these would be absent. The author states that: "It is obviously wrong to install power-factor-improving plant at a generating station. . . ." This appears to me to be too definite, for there are many occasions of long duration during periods of moderate load when the additional current due to poor power factor will be little detriment, so far as the carrying capacity of the cables and transformers is concerned, and which have a stabilizing effect on the voltage variation at the supply end, but which so far as the number of generators is concerned might necessitate an extra generator at the station to carry the wattless current. Under these circumstances power factor improvement at the generating station might easily release one generator during these periods. The period stated by the author over which the maximum demand should be taken, viz. 20–30 minutes, seems to be quite reasonable; but this appears to be another point on which uniformity amongst the supply authorities might reasonably be arrived at with advantage to all. The imposition of meter rent on large consumers appears to be another debatable point, in view of the fact that most large consumers provide a duplicate set of check meters which are of mutual benefit. It therefore appears equitable for the supply authority to provide one set of meters rent free.

**Mr. J. R. Williams :** Whilst agreeing that some method should, if possible, be adopted to penalize the consumer who is responsible for a low power factor, it is very questionable whether the method put forward in the paper, which is based upon the two variables, power factor and load factor, would be quite so simple and satisfactory as the author suggests. Electricity, like every other commodity, is subject to the laws of supply and demand, and what the consumer requires is a plain, simple and easily understood method of calculation. Many of us can remember the trouble that used to occur with the old maximum-demand indicator, and the present trouble in the gas industry over the so-called "scientific" method of charging by therms, instead of by cubic feet, gives us due notice of what we must expect from such a basis of charges as put forth in the paper. The consumer naturally considers that the so-called "scientific" basis is simply a trick to increase the price of the commodity, and there is no doubt that he is right in so far as it opens the door to such an increase, if desired. Table 2 is a case in point. First, the basic price is based upon pre-war conditions, and therefore under the present circumstances is from 50 to 70 per cent below the present actual prices. A table of costs of 20 of the largest generating stations in the country shows that the all-in costs vary from 1d. to 1·88d. at the present time (see *Electrical Times* tables). Secondly, the majority of small consumers (undoubtedly the small induction motor gives the greatest trouble) think that this term means that motors must be run at half load, whilst actually to obtain this impossible figure a motor must be run fully loaded for 12 hours per day and 365 days per annum—a distinction with a very big difference to the average consumer. The average power factor is much nearer 20 per cent than 50 per cent, and this at once increases by 150 per cent the price shown in Table 2, and it will be difficult to explain to a new consumer who has been told that Table 2 will give his probable cost, why his actual cost was three times as much. Dissatisfied consumers of this type are very detrimental to a supply department. Therefore, with all its faults, there is something to be said for the present rough-and-ready method of charging which, after all, is simple and easily understood. As a general rule, it is safe to assert that the power factor of induction motors decreases as the load decreases, and therefore that a lightly loaded motor gives rise to a low power factor. This is due to the fact that two currents have to be supplied, one for producing the mechanical energy and the other for magnetization purposes. The first is, of course, in phase with the supply voltage and the latter is in quadrature. The magnetizing current is practically constant for all loads, and it therefore follows that the greater the load the higher the power factor. A table based purely on the average load on the motor against the maximum specified load, would give a simpler method of calculation than that put forward in the paper.

**Mr. W. T. Wardale :** Whilst agreeing that the power user with a bad power factor is a serious nuisance to the public supply authority, I do not hold with the methods suggested by the author or by two speakers in the discussion who have advocated special rates, methods of calculation, or special instruments, for the determination of the penalty to be inflicted on the power user having a low power factor. The matter really divides itself into two fairly distinct problems. One is the large power consumer, who usually has a well-paid engineer in charge of his engineering, and who is thus able to obtain all the benefits from providing a good power factor which the supply people may offer, and who is also able to discriminate between applications of power factor correction which will cost more to apply than they will save, and those means, some of which are referred to in the paper, which enable the large power user to make considerable economies and, at the same time, to benefit the supply authority. These people can, and do, look after their interests. The second class of power user is the man with a small works, who often runs a 25 h.p. motor on a 20 h.p. job, and who will buy a motor because it is low in first cost and gives a margin above what he requires at the moment, and so will enable him to face a rush of work, or a slight extension of his shops, without purchasing any further motors. These people are, in the aggregate, the greatest offenders. Those who cannot understand any scientific basis of charging will see in such methods merely a means of trapping them into heavier charges, the reason for which they cannot understand. It will pay far better to set one's charge for such small motors on the basis of a power factor of 0·6 and to offer concessions to those consumers who will buy and install corrective apparatus. That this is now practically possible is shown by Dr. Wall's contribution to the discussion. Any system of special meters is too costly to consider, and leads to uneasiness on the part of the consumer. The method of finding the amount of kVA is simple to an electrical engineer and a mystery to nearly everyone else; therefore its use in this connection is not advisable. The system of charging must be easily comprehended. Another point to be noted is that the ordinary consumer does not realize that a 50 per cent load factor means 50 per cent load factor on 24 hours × full load × 365 days. We as electrical engineers do understand that fact, and we should be careful to point it out to those who use our energy. The owner of a works running 47 hours a week considers that he is giving a 50 per cent load factor if his motor runs at half load all his working hours; to such a man the table given would appear misleading.

**Mr. H. E. Yerbury** (*in reply*): I agree entirely with Mr. West's remarks, which are based on his actual experience in large works. The capital and running costs of power-factor-improvement devices are much less than the cost of a bad power factor, hence their installation must result in cheapening electricity. The supplier should, I think, be prepared to advise consumers as to how a good power factor may be brought about, and also to show what difference it would make in the electricity bill.

I agree with Mr. Burnand that it is desirable that a consumer's accounts should show separately kVA-hour units and kWh units, but I think it should be clearly understood that a supply authority is not desirous of selling wattless kVA units. I disagree entirely with the view that the maximum-demand system is fundamentally wrong, for the lowest price per unit to consumers invariably takes place under this system of charging, and all consumers have the means available of decreasing their maximum demand by phase advancing. The capital outlay for this plant is usually paid off in two to three years. As Mr. Burnand is a motor manufacturer, his views are naturally different from those of suppliers and the majority of consumers.

Mr. Jepson and Mr. James point out the difficulties in obtaining accurate measurements of all the factors on which a kVA demand should be obtained. It is, however, generally felt that the happy mean can be obtained in a fairly simple manner, and if this is satisfactory to both supplier and consumer the desired result is accomplished.

I am very pleased to hear that my remarks as to the absence of a cheap, simple and effective phase advancer suitable for small motors were unfounded. Since the paper was written I have had an opportunity of testing Dr. Wall's electrolytic phase advancer (which introduces capacity effects by a leading reactance voltage) on a 4 h.p. motor, and I can testify as to its behaviour. It has been in daily operation for the past three months unattended and has produced remarkable results, as shown by the curves and oscillogram. It is now being subjected to an endurance test, the result of which will be followed with much interest. This device emphasizes the important point that for the same power factor improvement only about one-thirtieth of the injected kVA is required in a rotor, as compared with a device operating on the high-frequency stator side.

I am in entire agreement with Mr. Fletcher's remarks, and recent improvements in the design of squirrel-cage rotors embodying two windings have reduced the starting current considerably. It may therefore be expected that squirrel-cage motors of larger capacity will be used to a great extent in the future. This will tend to improve the power factor. Mr. Fletcher also rightly points out that the capacity of a motor should be determined by the usual load it has to carry and not by the possible maximum.

Mr. Chaytor's remarks as to the absence of anything approaching standardization of tariffs and methods of charging for electrical energy will be generally endorsed. In my opinion his observations on the difficulty in maintaining uniform working conditions in works justify the desirability of measuring, resetting and charging monthly maximum-demand accounts so that any consumer in a particularly bad month would pay a correspondingly lower maximum-demand charge. Under exceptional conditions a minimum annual charge might reasonably be demanded.

I agree that it is manifestly unfair to call upon a consumer to pay a high maximum-demand charge if this is brought about by low frequency or low pressure. These two disturbing influences are happily infrequent, and under the Electric Lighting Acts the consumer has a remedy against the supplier if the variation of supply pressure and frequency are more than 4 per cent and 2½ per cent, respectively. Mr. Chaytor's method of changing motor connections from delta to star when running on light load could be adopted with advantage by many consumers.

I still submit that whenever it is possible to install power-factor-improving plant at a consumer's works or in substations or at the end of long transmission lines it should be placed there instead of at a generating station.

In reply to Mr. Williams and Mr. Wardale, I do not agree that the magnetizing current of a motor is practically constant for all loads, as this may vary up to 20 per cent and sometimes more. I am inclined to think that they are not familiar with present-day costs of electricity and the thousands of installations where the maximum-demand system is the basis of charging, hence they submit arguments for continuing in their belief.

At the present moment under the maximum-demand basis of charge in Sheffield some consumers pay between 0·5d. and 0·6d. per unit (which includes a coal increase of 0·166d.) and this total price could be lowered if power-factor-improving plant were installed. Under the flat rate, the price per unit at the same load factor would be more than double. Another Sheffield firm is saving about £3 000 per annum since the installation of power-factor-correcting plant.

I think that the time is fast approaching when a consumer will be at liberty to take from his single service, energy for power, heating or lighting, etc., and I submit that the two-part tariff is the best, simplest and most equitable under these conditions for both supplier and consumer.

## NORTH MIDLAND CENTRE, AT BRADFORD, 6 MARCH, 1923.

**Mr. H. F. Buttenshaw**: The following case, which came under my notice, may be of interest. One of the conditions under a new contract was that a compensator had to be employed for raising the power factor from 0·65 to 0·8, and the consumer therefore installed a 50 kW Crompton auto-synchronous motor, coupled to a d.c. generator. In consideration of this being done the Corporation offered him a considerably reduced tariff, representing a saving of approximately 50 per cent. Moreover, the effective transformer capacity has been increased by about 30 per cent and there has been a general improvement in the running of the numerous induction motors installed in the factory.

**Mr. R. M. Longman**: I think that the author might have extended Fig. 1 to include a power factor of 50 per cent. I have had several consumers with that power factor and, unless there is kVA tariff which they fully appreciate, it is most difficult to deal with such consumers. The author has chosen a case showing large figures, 80 000 and 20 000 kW. The argument holds good even with smaller figures of the same ratio, but the former are more likely to attract attention. I fail to understand his figures about the net return, nor do I follow his comparison of municipal and power companies' tariffs; I am not sure which the author thinks to be correct practice. Power companies have to consider very carefully at what figure they can give a supply at any specified point. Consumers at an outlying point cannot expect to be supplied at the same rates as those close to the power station; the latter condition more often prevails in a municipal supply. The statement on page 676, that power factor has great influence on the cost, is correct, but it is difficult to induce a consumer to improve his power factor unless one can show him that some saving will be thereby effected. Economy and general improvement are effected in several ways: (1) Reduction in kVA and in the kVA charges, the supply undertakings thereby contributing to the cost of the power-factor-improvement gear. (2) Improved voltage regulation, more uniform speed of motors and better output therefrom. (3) Increase of supply available at the point in question. Referring to the last item, it is the general practice for the consumer to provide accommodation for the transformer, etc.; with improvement of the power factor it becomes permissible to take a greater load from the transformer, which in some cases would otherwise have to be replaced by a larger one. This replacement, in turn, would necessitate increased accommodation and perhaps involve building expenditure. In several actual cases the cost of the power-factor-improvement apparatus has been defrayed in two years by the reduction in the kVA charges. The author states that it is obviously wrong to install power-factor-improvement plant at a generating station. Although his statement is correct in principle it is sometimes an advantage to run a generating set over-excited as a synchronous condenser in order to deal with the wattless current, thus obtaining the maximum kilowatt output from more economical generating plant. The statement that transformers do not take a large wattless component needs a little qualification, as that component depends on their design, the voltage at which they are operated, and the quality of the iron. In a number of transformers built during the war the iron was not all that could be desired, with the result that ageing has occurred, and the iron losses and magnetizing current are considerably increased. Another statement requiring some explanation is that it is better to work a motor on light load occasionally than to work it on full load occasionally; it all depends on the definition of "occasional" and the load during the "non-occasional" period. With regard to the question of tariffs, many years' experience of the kW maximum-demand system convinced me that it is not correct. The question of power factor correction is very well dealt with in one of Messrs. Pitman's technical primers entitled "Power Factor Correction" by A. E. Clayton. Money is well spent in purchasing a copy for presentation to a consumer with a poor power factor. I am also in full agreement with the author when he says, "Very little useful purpose is served if power factor conditions and regulation clauses are drawn up in such a manner that they cannot be enforced"; it is high time that such cases, which have been lying dormant for years, should be seriously tackled. With reference to the question of the type of apparatus to be used for ascertaining kVA demand, after consideration of all the possible methods one is forced to admit that the thermal demand indicator has much in its favour. It has reasonable accuracy; it is cheap, simple and easily fixed and understood. Another system which is used to a considerable extent consists of obtaining the maximum kW demand by means of a Merz indicator and converting this to kVA by dividing by the average power factor. Whilst this takes into account the voltage at the time of maximum demand, the consumer may be penalized by the use of the average power factor, because in all probability the power factor at the time of maximum load will be higher than the average power factor. I think, as regards metering, that the balanced-load polyphase meter should not be used. The equality of the currents in magnitude and phase displacement in the three phases cannot be guaranteed. The two or the three wattmeter method of metering should be used in all cases. With regard to the use of condensers for power factor improvement, I know of a group of collieries in which a number have been installed at intervals since 1913 on a 3 000 volt distribution system; they have given entire satisfaction, the maintenance has been practically nil, and their adoption has increased the capacity of transmission lines, etc., by at least 30 per cent.

**Mr. S. E. Hall**: The last speaker has talked about penalizing the consumer. The consumer, however, thinks that he has already been sufficiently penalized. In my opinion supply companies and not consumers will have to tackle this subject, for the reason that it is the former who appreciate and feel the difficulty and it is to their advantage to improve the power factor. It seems to me that in many cases the supply authority should be in the position to spend the necessary capital, charging the consumer for it, to the ultimate benefit of both. In some industries (the author has mentioned some particular cases) motors may constantly be reversing, the starting effort representing perhaps 60 or 70 per cent of the total time, and the starting effort may be two or three times the normal effort. I know of an instance where a 40 or 50 h.p. motor is installed, the normal load being approximately 10 h.p. In this case the consumer is willing to incur heavier charges for the sake of reliability.

**Mr. D. M. Buist** (*communicated*): The paper is a good attempt to overcome the seeming apathy of supply authorities towards this subject. Only in certain isolated cases has it been dealt with vigorously, and in these cases, needless to say, urgent necessity demanded action. The subject is an old one but it is becoming increasingly important, and therefore the more often it is brought to the notice of the industry the sooner will the dangerous policy of *laissez-faire* be abandoned. One might well ask what is the reason for this attitude. Is it the fear that the standardization of a method of charging on a kVA basis will raise a storm of public criticism similar to that recently encountered by the gas industry when the therm system of charging was inaugurated? If so, we must be prepared to face it, and, profiting by the experience of the gas engineers, we should educate the public consumers beforehand in the intricacies of the subject. It seems axiomatic to state, therefore, that whatever method of charging is adopted should (1) be as simple as the existing method; (2) require no more instruments than are at present used. Having warned the consumer that he is to be charged on a new basis—we must take care not to mislead him into thinking that we are adopting a new unit—the next step we have to take is to point out to him how he can reduce his accounts under the new system, possibly below his accounts under the old system, by the introduction of certain devices for power factor improvement. It would appeal more to the consumer if such devices were to be called "current savers." Further, a consumer will naturally view with suspicion any move on the supply undertaking's part to assist him in reducing his account, as to him such procedure would seem as if the undertaking were robbing its own pockets. Consequently he will have to be educated in the advantages of these so-called "current savers" not only to himself but to the supply undertaking also. This is what will constitute by far the greater and more difficult part of the problem, viz. to make the consumer understand that the steps we are advising him to take in order to reduce his account, will at the same time increase the capacities of our generators, switchgear and cables, and improve the efficiency and pressure regulation of the system. The author would have added to the value of his paper had he put forward some suggestions for the formulation of a standardized system of charging. Would it not be possible for the Institution to convene a special meeting, at which could be appointed a sub-committee to tackle the problem immediately? Such a step has already been taken in the electrical industry in Germany, but, despite the equal seriousness of the matter in this country, it is to be regretted that it seemingly has not yet advanced beyond the "pet subject" stage, except in those cases already referred to where a few pioneers are taking preliminary measures. I notice that the author does not advance any opinions for or against the respective methods of measuring kVA. It should be borne in mind that what is wanted is an instrument or an arrangement of meters capable of giving, over any period of time, the average power factor during that period. The arrangement which seems to be most favoured in this country is that consisting of two single-phase integrating wattmeters, and this arrangement is recommended by the author. The method is certainly not so accurate as others, but it possesses the advantage of being simple, and can be used to check the reading of the main meter. I agree with the author when he states that recording power factor meters, wattless-component meters, and kVA maximum-demand indicators of the thermal type are expensive, and in addition are too complicated to be understood by the consumer. It seems rather futile to make stipulations with regard to average power factor in any regulations when, as is the case with some undertakings, no means are provided for measuring the average power factor. Other undertakings measure the power factor on inspection, but the criticism of this system is that the measurement may be made at an unsuitable moment and with instruments of disputable accuracy. With regard to what constitutes a good average power factor, the general feeling seems to be that power factors below 80 per cent should be corrected or the consumers penalized. With reference to devices for correcting low power factor, prevention is undoubtedly better than cure, but as the preventive measures which we possess at present are applicable only to large motors, our attention must be of necessity confined to individual large consumers. In the case of the small consumers the suppliers themselves must provide a collective remedy at such convenient points as substations, by installing either static or rotary condensers in parallel with the low-tension load. In this respect, as pointed out by the author, rotary converters and motor converters in substations can be employed under certain circumstances to neutralize a lagging power factor. As a last resource, the correction can be made at the generating station itself. I regret to note that the author has not included in his list of typical examples of power factor correction that of a rotary synchronous condenser, and to fill the gap I give similar particulars of an installation of which I know.

| Installation | Capacity of rotary condenser | Original power factor | Improved power factor | Total cost (approx.) |
|---|---|---|---|---|
| 3 000 kVA plant increased by 1 500 kVA turbo-alternator | A. 1 500 kVA | 0·70 | 0·90 | £3 500 |
| | B. 3 400 kVA | 0·70 | 1·00 | £8 000 |

My reason for giving this case is in order to exemplify the commercial impracticability of striving for unity power factor in all cases. In this particular case it was finally decided that, owing to first cost, improvement of the power factor beyond 90 per cent was not warranted.

**Mr. H. E. Yerbury** (*in reply*): I am interested to learn from Mr. Buttenshaw that a municipal electricity department has reduced its price per unit approximately 50 per cent to a consumer who has raised his power factor from 0·65 to 0·8 by installing a 50 kW synchronous motor. This is a far higher percentage saving than recommended in the paper, and more than I think is justifiable.

In reply to Mr. Longman regarding my remark as to a net return of at least £1 500 per annum from a 15 000 kW connected load, by net return is meant net profit to a municipality after putting aside, say, 5 per cent for interest, 3 per cent for sinking fund, and a reasonable sum for renewals and obsolescence. A supply company would declare a net profit after meeting ordinary charges plus a sum for depreciation and renewals. Another difference between a company and a municipality appears to me to be the longer view invariably taken by a company in, say, the laying of mains to outlying districts where the immediate revenue does not pay for the capital expenditure, in which case an electric supply committee would possibly refuse to give a supply without a guaranteed minimum revenue. A municipal department has no statutory powers to give a supply at a lower rate to a consumer whose works are situated close to a power station. My remark that it is better to work a motor on light load occasionally than on full load occasionally is made as a result of observations of works where it is the practice to install motors far too large for the service requirements and where full load occurs only during the starting up of the plant. Under these conditions low power factor is the result. I still submit that in proportion to their output and compared with induction motors which require a wattless component of 25 per cent and upwards of their kVA rating, transformers do not take a large wattless component. Unsuitable iron was undoubtedly used during the war, with the result that losses have increased with age. From periodical tests made in Sheffield of Hadfield's "Stalloy" steel containing 3·4 per cent of silicon in transformers built in 1905–6, the total losses, for some unknown reason, have actually decreased with age. Mr. Longman's decision that a kW maximum-demand system is incorrect is encouraging, and I agree that the balanced-load polyphase meter should not be used.

Mr. Hall raises the question as to whether the supplier should correct low power factor and charge the consumer on the necessary capital expenditure. This could be done in individual cases, but if applied to the whole of the consumers it would obviously be unfair to increase the price per unit to those who had laid down their plant on good engineering lines and now take current at about 0·8 power factor. The instance cited of the normal load of a motor being 10 h.p. and a 40 to 50 h.p. motor being installed for the sake of so-called reliability, is a specific instance of "over-motoring" for which the consumer should be penalized for low power factor. A motor should withstand a fairly high overload and temperature-rise and still be absolutely reliable, and I think that the normal rating should be less than its possible intermittent maximum load.

Mr. Buist would like to know whether a standardized method of charging on a kVA basis would raise a storm of public criticism. I anticipate that only where the ultimate price per unit would be increased would any criticism be forthcoming, and I venture to think that if an attractive form of tariff could be evolved so that electricity could be used freely and cheaply for all purposes, general satisfaction would result. Only by increasing the all-round efficiency, by the better utilization of the plant, can capital charges be reduced and the selling price of electricity lowered.

It is suggested that no standardized system of charging was put forward in the paper. I submitted that a simple unit charge was inequitable and that a uniform kVA two-part tariff was in my opinion the most desirable on the grounds of efficiency and equity. For cheapness and simplicity I think that the thermal demand indicator is to be recommended for general purposes, plus a sine meter and a cosine meter. I agree that to attempt to ascertain the average power factor of any installation on a casual inspection of an indicator is useless.

The appendix to the paper shows the comparative energy losses of a static and a rotary synchronous condenser; as the losses in the latter are 10 times those in the former the use of the synchronous condenser has been very restricted. As to whether it is undesirable commercially to raise the power factor to unity depends entirely on local conditions and, apart from the use of rotary converters, it is generally thought that unity is too high an attainment from a purely commercial standpoint.

# THE PULLING INTO STEP OF AN INDUCTION-TYPE SYNCHRONOUS MOTOR.*

By LAURENCE H. A. CARR, M.Sc.Tech., Member.

(*Paper first received* 27*th October*, 1922, *and in final form* 1st *January*, 1923.)

SUMMARY.

The paper gives a mathematical determination of the limiting conditions under which an induction-type synchronous motor will pull into step.

In a recent paper[†] the author gave an approximate solution for the limiting conditions under which the synchronization of an induction-type synchronous motor was certain.

Further work has been carried out on the subject, with the result that a full practical solution can now be given.

LIST OF SYMBOLS.

Let $T_m$ = maximum synchronous torque, in pounds-feet;
$T_l$ = load torque, in pounds-feet;
$\mathbf{I} = Wr^2/g$, in pounds, feet and seconds;
$t$ = time, in seconds;
$p$ = number of pole-pairs;
$\omega$ = slip at load $T_l$ as an induction motor, in mechanical radians per second;
$p\omega$ = slip at load $T_l$ as an induction motor, in electrical radians per second;
$\alpha$ = angle of lag of centre of pole of rotor behind synchronously rotating flux, in mechanical radians;
$p\alpha = \beta$ = angle of lag of centre of pole of rotor behind synchronously rotating flux, in electrical radians;
$\rho = T_l/T_m$;
$\psi = \text{arc} \sin \rho$ [Note: $\psi$ lies between 0 and $\pi/2$];
$\theta_2 = \pi - \psi$;
$\theta_1 = -\pi - \psi$;
$\theta_0 = \text{arc} \sin (-0{\cdot}57\rho)$ [Note: $\theta_0$ lies between 0 and $-\pi/2$];
$\omega_0$ = maximum value of slip, in mechanical radians per second;
$p\omega_0$ = maximum value of slip, in electrical radians per second.

Considering synchronism as the point of view, and measuring motoring torques in a positive sense, while the angle of lag of the rotor is also measured in a positive sense, we have:—

Load torque $= -\rho T_m$.

Synchronous torque $= T_m \sin p\alpha = T_m \sin \beta$.

Induction torque $= \dfrac{T_l}{\omega} \cdot \dfrac{d\alpha}{dt} = \dfrac{T_l}{p\omega} \cdot \dfrac{d\beta}{dt}$.

Acceleration (acting in the contrary direction to the slip) $= -\dfrac{d^2\alpha}{dt^2} = -\dfrac{1}{p} \cdot \dfrac{d^2\beta}{dt^2}$.

Hence
$$-\rho T_m + T_m \sin \beta + \frac{T_l}{p\omega} \cdot \frac{d\beta}{dt} = -\frac{\mathbf{I}}{p} \cdot \frac{d^2\beta}{dt^2} \quad . \quad (1)$$

This can be transformed into
$$-\rho T_m + T_m \sin \beta + \frac{\rho T_m}{p\omega} \cdot \frac{d\beta}{dt} + \frac{\mathbf{I}}{p} \cdot \frac{d^2\beta}{dt^2} = 0 . \ (2)$$

Since this equation also represents under certain circumstances the swinging of a rigid pendulum round a complete circle in a vertical plane, the physical meaning of the various factors may be more easily followed if reference is made to such a pendulum system, which thus forms a mechanical analogy to the phenomenon of synchronization.

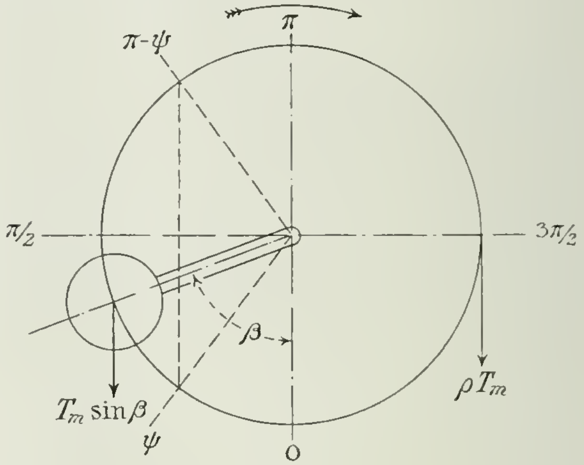


FIG. 1.

Such a pendulum is shown in Fig. 1, the condition of slip being represented when the pendulum rotates in a clockwise direction. $\beta$ and $d\beta/dt$ are called positive under this condition, $\beta$ being zero when the pendulum hangs vertically downward. The condition of rest represents synchronism.

Torques are measured in a counter-clockwise direction. $T_m$ is the maximum torque exerted by the pendulum, i.e. weight multiplied by radius, and $T_l$ is the "load" torque tending to drive the pendulum in a clockwise direction, which equals $-\rho T_m$ when measured in a counter-clockwise sense.

Frictional torque is imagined to exist and to be proportional to the speed, $\rho T_m$ being the frictional torque when $d\beta/dt = p\omega$, and $\mathbf{I}/p$ the moment of inertia of the combination about the axis of rotation of the pendulum.

If $\rho$ is less than $1{\cdot}0$ then, just as in the case of the synchronous induction motor, there will be two values of $\beta$ when $\rho T_m$ balances $T_m \sin\beta$, one being stable and the other unstable.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] "Induction-Type Synchronous Motors," *Journal I.E.E.*, 1922, vol. 60, p. 165.

The stable position occurs when $\rho = \sin\beta$ and $\beta$ is less than $\pi/2$. The unstable position occurs where $\rho = \sin\beta$ and $\beta$ lies between $\pi/2$ and $\pi$. In these two positions $\beta = \psi$ and $\beta = (\pi - \psi)$, respectively.

If the pendulum is at rest in the unstable position where $\beta = \pi - \psi$, which may also be written $\beta = -\pi - \psi$, and is moved ever so slightly in a clockwise direction, it will swing right round, and the critical case (which is the critical case for synchronization in the motor) occurs when the factors are such that the pendulum just comes to rest again at $\beta = (\pi - \psi)$, for if it fails to reach this point it will swing back and eventually settle at $\beta = \psi$, while if it swings past this point it will continue to swing round indefinitely.

It is then required to solve Equation (2) (which is true whether the machine synchronizes or not) for the special case described above, when $d\beta/dt = 0$, both for $\beta = \theta_1 = -\pi - \psi$ and $\beta = \theta_2 = \pi - \psi$.

Equation (2) may be rewritten in the general form

$$a + b\sin\beta + c\frac{d\beta}{dt} + d\frac{d^2\beta}{dt^2} = 0 \quad . \quad . \quad . \quad (3)$$

where $a = -\rho$; $b = 1\cdot0$; $c = \rho/p\omega$; and $d = \mathbf{I}/T_m p$.

If $y$ be put equal to $d\beta/dt$

then $$\frac{d^2\beta}{dt^2} = \frac{dy}{dt} = \frac{dy}{d\beta}\cdot\frac{d\beta}{dt} = y\frac{dy}{d\beta}$$

and Equation (3) becomes

$$a + b\sin\beta + cy + dy\frac{dy}{d\beta} = 0 \quad . \quad . \quad (4)$$

Direct mathematical solutions of either of these equations appear to be impossible, despite a great deal of labour spent in attempting solutions by the aid of various types of series, and a step-by-step method had to be evolved, in which the constants were varied until a curve was obtained which had the desired property of $d\beta/dt = 0$ at both $\beta = \theta_1$ and $\beta = \theta_2$.

Filling in the constants $a = -\rho$ and $b = 1\cdot0$, Equation (4) becomes:—

$$-\rho + \sin\beta + cy + dy\frac{dy}{d\beta} = 0 \quad . \quad . \quad (5)$$

$$\frac{dy}{d\beta} = \frac{\rho - \sin\beta}{dy} - \frac{c}{d} \quad . \quad . \quad . \quad . \quad (6)$$

But for a step-by-step curve over the range from $(\beta_1, y_1)$ to $(\beta_2, y_2)$, $dy/d\beta$ must be replaced by $(y_{-} - y_1)/(\beta_2 - \beta_1)$, while the mean value of $y$ becomes $(y_2 + y_1)/2$ and the mean value of $(\rho - \sin\beta)$ for each step may either be read off a curve or calculated by an easy integration.

Equation (6) then becomes

$$\frac{y_2 - y_1}{\beta_2 - \beta_1} = \frac{2(\rho - \sin\beta)}{d(y_2 + y_1)} - \frac{c}{d} \quad . \quad . \quad . \quad (7)$$

This leads to a simple quadratic equation

$$y_2 = -M \pm \sqrt{(M^2 - Q)} \quad . \quad . \quad . \quad (8)$$

where $$M = c(\beta_2 - \beta_1)/2d \quad . \quad . \quad . \quad . \quad (9)$$

and

$$Q = cy_1(\beta_2 - \beta_1)/d - y_1^2 - 2\{(\rho - \sin\beta)(\beta_2 - \beta_1)\}/d \quad (10)$$

Since when $\beta_2 - \beta_1 = 0$, $y_2 = y_1$, the positive sign only in Equation (8) should be taken.

Equation (8) is still further simplified if the figure for $(\beta_2 - \beta_1)$ is filled in; and if 30° steps are taken, that is to say $(\beta_2 - \beta_1) = \pi/6$ radians, Equations (8) to (10) reduce to

$$y_2 = -0\cdot263\frac{c}{d} + \sqrt{\left[\left(0\cdot263\frac{c}{d}\right)^2 - \left\{0\cdot524\frac{c}{d}y_1 - y_1^2 - \frac{1\cdot047}{d}(\rho - \sin\beta)\right\}\right]} \quad (11)$$

These equations allow the curve of $y$ against $\beta$ to be drawn to any desired degree of accuracy, by simple step-by-step calculations from the point $\beta = \theta_1$, $y = 0$.

With given constants $d$ and $\rho$, in order to obtain the critical curve, the constant $c$ has to be modified by trial and error until the curve is obtained such that $y = 0$ at $\beta = \theta_2$.

Fig. 2 shows the critical curve obtained when $\rho = 0\cdot5$ for a machine with the constants $T_m = 2\,000$, $\mathbf{I} = 200$, $p = 5$, and $d = \mathbf{I}/T_m p = 0\cdot02$, and in order to make the curve close at $\beta = \theta_2$, $c$ has been taken as $0\cdot0582$, that is to say $p\omega$, the slip at full load in electrical radians per second, is $8\cdot58$. In this figure the induction motor torque

$$\frac{\rho T_m}{p\omega}\cdot\frac{d\beta}{dt}, \text{ or } \frac{\rho T_m}{p\omega}y$$

is plotted positively.

The retarding torque (load torque minus synchronous motoring torque) is also plotted positively, so that the difference between the two curves gives the curve of the net torque producing the oscillation. The scale of $y = d\beta/dt$ is so drawn relatively to the torque scale that the same curve represents both slip and induction torque. The time scale can be determined by calculating $1/y$ (that is, $dt/d\beta$) for successive points and plotting $dt/d\beta$ against $\beta$. The integral of this curve

$$\int\frac{dt}{d\beta}d\beta = \int dt = t + \text{constant}$$

so that by graphic integration of a curve showing $dt/d\beta$ or by a corresponding continuation of the step-by-step calculation, the time scale can be obtained, any arbitrary point being selected as zero.

The curve of speed against time obtained in this manner for the foregoing example is given in Fig. 3, and if continued would extend to infinity in both directions before synchronism is actually reached.

In the case of the synchronous induction motor, before switching on the field current the machine is running at its induction-motor speed. If the excitation is switched on at the angle of rotor lag $\beta$ corresponding to the induction-motor speed in the oscillation shown in Fig. 3, the machine immediately follows the speed curve shown in that figure.

If the excitation is switched on at some other angle of lag, the effect on the speed curve is similar to the well-known "switching effect." For example, if the excitation is switched on at a point corresponding to a lower speed (greater slip) than the induction-motor speed, the curve is raised, and the machine will easily synchronize on the first swing. If, on the other hand, the excitation is switched on at a position corresponding to a higher speed (less slip) than the induction-motor speed, the machine will fail to synchronize on the first swing. In this case, however, the mean induction-motor slip, and hence the torque averaged over the double pole-pitch, will be greater than the full-load figures, that is to say the machine will accelerate and slowly climb back to the case shown, synchronizing after a theoretically infinite number of oscillations.

The case shown is therefore the critical case, i.e. the case of the maximum possible induction-motor slip at full load when ultimate synchronization is certain, whatever be the time of switching on the excitation.

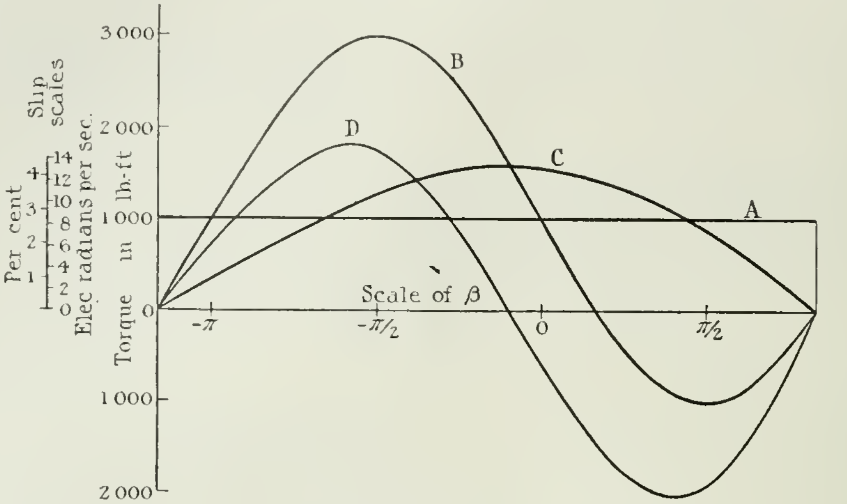


FIG. 2.

Curve A: Load torque.
,, B: Load torque less synchronous motoring torque.
Curve C: Induction motoring torque and slip
,, D: Net oscillating torque.

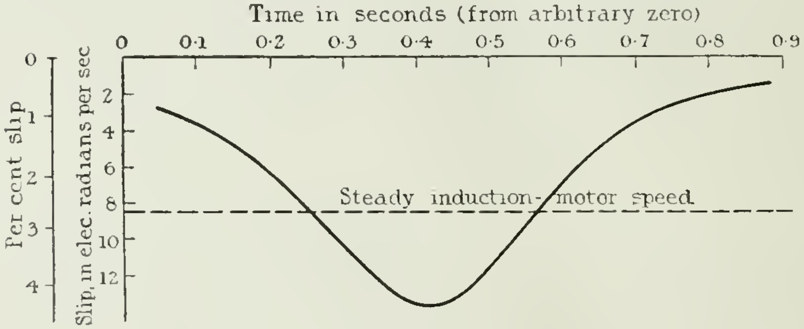


FIG. 3.

Returning to Fig. 2, the curve of induction torque has the following characteristics:—

(1) Since the synchronous torque adds up to zero over the cycle, the area of the induction torque curve must be the same as the area of the load curve.

(2) Where the induction torque curve crosses the (load minus synchronous motoring torque) curve, as drawn in Fig. 2, the total torque is zero, the slip is a maximum, and hence the induction torque curve must be a maximum at this point.

(3) The curve of induction torque cannot run to a sharp apex, but must have a smooth curve at its maximum, which must therefore be less than twice the mean value unless there are correspondingly big hollows in the lower branches of the curve.

It appears from the curve shown in Fig. 2 that the maximum of the induction torque curve bears almost exactly the same relation to its mean value as does the maximum of a sine wave to its mean value. In other words, each half of the induction torque curve is approximately a quarter sine-wave, the base in one half being extended, and in the other half compressed. Consequently the maximum slip is 1·57 times the mean slip, where the mean slip is averaged over the double pole-pitch.

While Fig. 2 only shows that this assumption is true for $\rho = 0\cdot5$, the characteristics of the induction torque curve laid down above indicate that it must be approximately true also for all values of $\rho$. It therefore follows that at maximum slip the synchronous torque must be $-0\cdot57\rho T_m$ for the torques to balance. This fixes the position for the maximum slip condition, and the work done in acceleration on the one side of this position is equal to the work given out in deceleration on the other.

Since $\theta_1 = -\pi - \psi$, $\theta_2 = \pi - \psi$, and $\theta_0$ (the position of maximum slip) $= \text{arc}\sin(-0{\cdot}57\rho)$, where $\theta_0$ lies between 0 and $-\pi/2$, the work done by deceleration of the pendulum (or in accelerating the rotor from maximum slip speed to synchronism), which takes place between $\beta = \theta_0$ and $\beta = \theta_2$, equals

$$T_m \int_{\theta_0}^{\theta_2} \left(-\rho + \sin\beta + \frac{\rho}{p\omega}\cdot\frac{d\beta}{dt}\right) d\beta \quad . \quad . \quad (12)$$

But $\dfrac{T_m\rho}{p\omega}\cdot\dfrac{d\beta}{dt}$ is, by the foregoing assumption, equal to

$$1{\cdot}57\rho T_m \sin k(\theta_2 - \beta)$$

where $k = (\pi/2)/(\theta_2 - \theta_0)$.

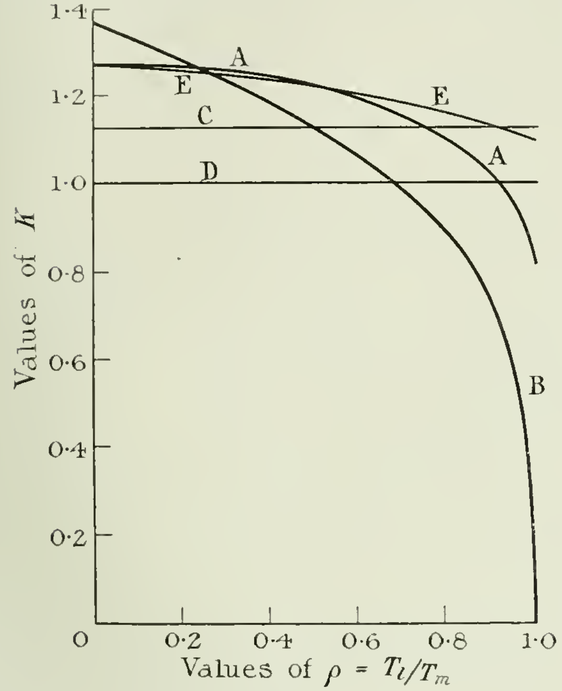


Fig. 4.

Curve A: Carr: $\sqrt{[0{\cdot}81(\cos\theta_0 - \cos\theta_2)]}$.
,, B: Carr's first approximation, *Journal I.E.E.*, 1922, vol. 60, p. 165.
,, C: Otto Böhm: *E.T.Z.*, 30 March, 1922.
,, D: Rosenberg: *Journal I.E.E.*, 1913, vol. 51, p. 71.
,, E: Dreyfus: *Elektrotechnik und Maschinenbau*, 1922, vol. 40, p. 457.

Therefore work done

$$= T_m \int_{\theta_0}^{\theta_2} \left\{-\rho + \sin\beta + 1{\cdot}57\rho \sin k(\theta_2 - \beta)\right\} d\beta \quad (13)$$

$$= T_m\left[-\rho\beta - \cos\beta + \left\{1{\cdot}57\rho\cos k(\theta_2 - \beta)\right\}/k\right]_{\theta_0}^{\theta_2}$$

$$= T_m\left[-\rho(\theta_2 - \theta_0) + (\cos\theta_0 - \cos\theta_2) + \left\{1{\cdot}57\rho\,(1 - \cos k\overline{\theta_2 - \theta_0})\right\}/k\right] \quad . \quad (14)$$

but $\quad k(\theta_2 - \theta_0) = \pi/2$

hence $1{\cdot}57\rho(1 - \cos k\overline{\theta_2 - \theta_0})/k = 1{\cdot}57\rho/k$

$$= 1{\cdot}57\rho(\theta_2 - \theta_0)/(\pi/2)$$
$$= \rho(\theta_2 - \theta_0)$$

so that work done $= T_m(\cos\theta_0 - \cos\theta_2) \quad . \quad (15)$

but the work given out by the pendulum in being decelerated

$$= \frac{1}{2}\cdot\frac{\mathbf{I}}{p}(p\omega_0)^2 \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where $p\omega_0$ is the velocity at $\beta = \theta_0$, i.e. $p\omega_0 = 1{\cdot}57p\omega$,

$$\text{hence work done} = \frac{1}{2}\cdot\frac{\mathbf{I}}{p}(1{\cdot}57p\omega)^2 = 1{\cdot}235\mathbf{I}p\omega^2 \quad (17)$$

Equating the two expressions for the same work we get

$$1{\cdot}235\mathbf{I}p\omega^2 = T_m(\cos\theta_0 - \cos\theta_2)$$

$$p\omega = \sqrt{[0{\cdot}81(\cos\theta_0 - \cos\theta_2)T_m p/\mathbf{I}]} = K\sqrt{(T_m p/\mathbf{I})} \quad . \quad (18)$$

where $p\omega$ is the limiting slip for synchronizing;
$\psi = \text{arc}\sin\rho$ = angle of stable equilibrium;
$\theta_2 = \pi - \psi$ = angle of unstable equilibrium;
$\theta_0 = \text{arc}\sin(-0{\cdot}57\rho)$ = angle where minimum slip occurs.

The following table of values of $K$ may therefore be calculated, the results being plotted in Fig. 4 in comparison with the approximate solutions obtained by various investigators:—

| $\rho$ | $\psi$ | $\theta_2$ | $\theta_0$ | $K$ |
|---|---|---|---|---|
| | deg. | deg. | deg. | |
| 0 | 0 | 180 | 0 | 1·27 |
| 0·1 | 5·75 | 174·25 | − 3·3 | 1·267 |
| 0·2 | 11·55 | 168·45 | − 6·55 | 1·262 |
| 0·3 | 17·45 | 162·55 | − 9·85 | 1·255 |
| 0·4 | 23·6 | 156·4 | − 13·2 | 1·238 |
| 0·5 | 30·0 | 150·0 | − 16·55 | 1·212 |
| 0·6 | 36·9 | 143·1 | − 20·0 | 1·185 |
| 0·7 | 44·4 | 135·6 | − 23·5 | 1·142 |
| 0·8 | 52·1 | 126·9 | − 27·1 | 1·10 |
| 0·9 | 64·15 | 115·85 | − 30·9 | 1·022 |
| 1·0 | 90 | 90 | − 34·75 | 0·815 |

This table, being based on the curves corresponding to $\rho = 0{\cdot}5$, is necessarily true for that value, but before it can be accepted as a complete solution it requires to be checked for the limiting values of $\rho = 0$ and $\rho = 1{\cdot}0$.

For $\rho = 0$, which in practice represents an oscillation where there is no induction motor torque available, the set being brought up nearly to synchronous speed by some outside source, Equation (2) simplifies to

$$T_m \sin\beta + \frac{\mathbf{I}}{p}\cdot\frac{d^2\beta}{dt^2} = 0 \quad . \quad . \quad . \quad (19)$$

This equation is capable of complete mathematical solution, as follows:—

$$\beta = 4\,\text{arc}\tan \epsilon^{\sqrt{(T_m p/\mathbf{I})}t} - \pi \quad . \quad . \quad . \quad . \quad . \quad (20)$$

$$\frac{d\beta}{dt} = 2\sqrt{\left(\frac{T_m p}{\mathbf{I}}\right)}\sin\left(\frac{\beta}{2} - \frac{\pi}{2}\right) \quad . \quad . \quad . \quad . \quad . \quad (21)$$

$$\frac{d^2\beta}{dt^2} = \frac{T_m p}{\mathbf{I}}\sin(\beta + \pi) = -\frac{T_m p}{\mathbf{I}}\sin\beta \quad . \quad . \quad (22)$$

Equation (21) shows that the shape of the curve of $d\beta/dt$, that is to say slip, plotted against $\beta$ is a half sine-wave, or, in other words, the assumptions made for $\rho = 0{\cdot}5$ become mathematical truths for $\rho = 0$, and the maximum value of $d\beta/dt$ which occurs when $\beta = 0$ is

$$d\beta/dt = p\omega_0 = 2\sqrt{(T_m p/\mathbf{I})} \quad . \quad . \quad . \quad (23)$$

The mean value of $d\beta/dt$ over the range from $\beta = -\pi$ to $\beta = +\pi$ is

$$p\omega = \frac{p\omega_0}{1{\cdot}57} = 1{\cdot}27\sqrt{(T_m p/\mathbf{I})} \quad . \quad . \quad (24)$$

as given in the above table.

Reference may here be made to Rosenberg's paper,* where this no-load problem is considered.

Also, it is well known that with absolutely no load (if such a condition could be realized in practice) an induction motor would accelerate right up to synchronism, and hence, if the torque per unit slip is large enough, there would appear to be no reason why a similar occurrence should not take place when the load torque is balanced by the maximum possible synchronizing torque.

Fig. 5 is calculated for the same motor as before, but with $\rho$ raised to $1{\cdot}0$ and $p\omega$ reduced to $5{\cdot}76$ radians per second to agree with the tabulated figure, the same step-by-step method of calculation being employed. It will be seen from the figure that the slip curve returns to zero at $\beta = \pi/2$, showing that the machine will just pull into step in an infinite time. Part curves indicating the falling out of step with no induction or damping torque, and the rising up to synchronous speed as an induction motor with no load and no synchronous torque, are also given in this figure.

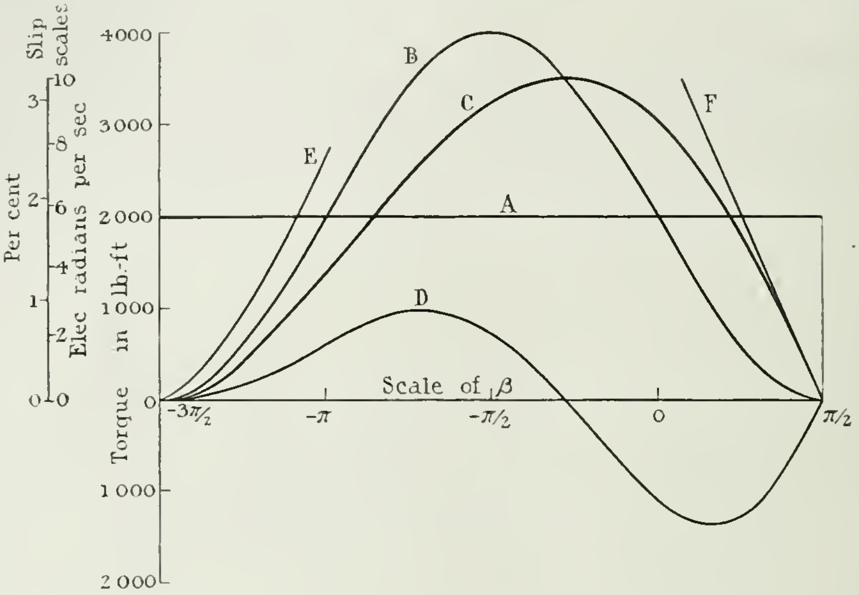


FIG. 5.

Curve A: Load torque.
,, B: Load torque minus synchronous motoring torque.
,, C: Induction motoring torque and slip.
Curve D: Net oscillating torque.
,, E: Slip (falling out of step); no induction torque.
,, F: Induction torque and slip; no load, no synchronous torque.

Simplified into the same type of equation and symbols as used above, it is found that Rosenberg's figure for maximum slip is identically the same as given in Equation (23), but in obtaining the value of mean slip, or necessary speed to which the machine must be brought by an outside source, Rosenberg falls into the error of assuming that the mean slip (with reference to $\beta$) is one-half the maximum value, and hence his final result for $p\omega$ is $\sqrt{(T_m p/\mathbf{I})}$, a result that is in error, as the above reasoning shows.

There remains the checking of the formula at $\rho = 1{\cdot}0$. At first sight it may seem unlikely that a synchronous induction motor should be able to synchronize against its pull-out torque. At the same time, if this should occur, the load and synchronous torques would exactly balance, leaving no load for the induction torque to take care of.

It will be seen that although the curve of induction motor torque is somewhat distorted from the simple shape on which the theory was founded, nevertheless the value of $p\omega$ obtained by the general equation is found to agree exactly within the limits of step-by-step draughtsmanship with the value of $p\omega$ corresponding to the actual curve of torque traced out by the machine.

The formula for limiting slip given in Equation (18) and illustrated in Fig. 4 may therefore be taken to be absolutely correct throughout the range from $\rho = 0$ to $\rho = 1{\cdot}0$.

Owing to the form in which this equation is written, it remains true, without any additional constant, whether $T_m$ and $\mathbf{I}$ are taken in metric or British units.

---

* "Self-synchronizing Machines," *Journal I.E.E.*, 1913, vol. 51, p. 71.

# A BRIDGE METHOD FOR DETERMINING DIELECTRIC LOSSES AT WIRELESS FREQUENCIES.[*]

By MORRIS D. HART, M.Sc., Student.

(*Paper first received* 1st *May, and in final form* 27*th November*, 1922.)

SUMMARY.

The method described below was devised with a view to the investigation of the losses which occur in soil.

The principle employed was that of a modified form of Wheatstone bridge, and a description is given of the arrangement of the apparatus used.

It was found possible satisfactorily to measure at various frequencies the capacity and equivalent resistance of the condensers employed, and the latter was found to be unexpectedly large.

Some suggestions are added that may be of service to those who contemplate similar work.

The general principle adopted in the method here described was to conduct the experiment throughout on the largest practicable scale, in order to reduce to a minimum such errors as those due to the capacity of the operator. Subsequent experience confirmed the belief that in this way the difficulties inseparably associated with these stray capacities are best surmounted.

The high-frequency current led into the bridge was produced by a circuit possessing no special features; a type T2B transmitting valve, consuming about 50 watts, was used as generator, and a vacuum-tube wave-meter was coupled thereto in order to measure the wave-length of the oscillations. This circuit was reduced to the smallest possible dimensions so as to avoid direct radiation to the detecting circuit, and was for the same reason placed at a considerable distance from the bridge, to which the current was led by wires traversing the room as near the ceiling and as far apart from each other as practicable.

The bridge was arranged as shown in Fig. 1, in which the condenser $C_1$ is that to be calibrated, and $C_2$ is a standard condenser degraded to the level of the former by means of a series resistance $R_3$. Thus the value of $R_3$ is a measure of the losses occurring in the condenser under test, and $R_1$ of the effective capacity, these values being of course taken when a balance has been obtained. Leads 1, 2, 3 and 4 were taken from the points shown and correspond to those of the same numbers in Fig. 2, and it will be seen that both the telephones and the point of the bridge touched by the operator could be earthed.

Since resistance boxes for $R_1$, $R_2$ and $R_3$ were clearly impracticable, these resistances were made of fine Eureka wires some 2 metres long and 50 ohms resistance, stretched about 1 metre above the bench. Connection was made to the variable resistances $R_1$ and $R_3$ by means of small cubical tanks, about 0·5 cm side, constructed of thin sheet copper and filled with mercury; in opposite sides of these were pierced fine holes through which the wire could pass without allowing the mercury to escape.

A number of different circuits were tried as detecting devices and proved unsatisfactory in one or more respects. The final arrangement is shown in Fig. 2.

It will be seen that three valves were used, the first amplifying on the high-frequency side, the second acting as a heterodyne generator, and the third as a low-frequency amplifier. It was found essential to employ two separate sets of high-tension batteries, one for the amplifying valves and one for the heterodyne generator, in order to avoid reciprocal interference effects which were responsible for the failure of some of the earlier circuits used. The inclusion of the heterodyne principle was found to be of the greatest importance as it affords a variation of *pitch* when the capacity of the appropriate condenser is altered, so long as the bridge is out of balance; and the absence of this effect is much easier to detect than is a minimum intensity of a sound of constant pitch.

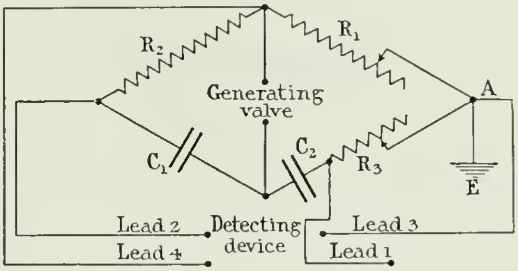


FIG. 1.—Arrangement of bridge.

Preliminary experiments showed, however, that the magnitude of the "angle of the condenser"[*] to be measured was of the order of several degrees and this involves a very high value of $R_3$, especially at long wave-lengths. Thus, it was necessary to sacrifice some of the simplicity of the bridge by providing resistances of constant value to be inserted in series with the variable resistance $R_3$. These were made up of No. 47 S.W.G. Eureka cut to lengths to give approximately 400, 300, 200, 100, 50 and 20 ohms. Since the actual resistance was always determined by a Post Office box (Fig. 2) the exact value of the resistance was immaterial. These fine wires were soldered to stout copper leads and attached to strong threads slightly shorter than themselves, in order to relieve them of tensional strains.

---

[*] The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[*] That is to say, the complement of the angle by which the current through the condenser leads the voltage across it.

A series of readings was taken with this apparatus from wave-lengths of about 2 000 to 15 000 m. For wave-lengths greater than these, reliable results could not be obtained as the sound became so small that adjustments of the series resistance were rendered almost impossible. The method of dealing with the results was as follows :—

The readings of $R_1$ and $R_3$ (Fig. 1) were plotted separately (Figs. 3 and 4) against the wave-length, and fair curves were drawn through these points. In the figures the points marked X are actual readings, and the points marked with a small circle thus, O, are on the curves that were used for purposes of calculation. All the readings taken in the series mentioned above appear in the figures. The values of $R_1$ and $R_3$ were then taken from the curves at points O and tabulated ; and from them were calculated the values of (1) frequency, (2) $\tan\theta = \omega C_2 R_3$ (where $\theta =$ the angle of the condenser, $\omega = 2\pi$ times the frequency, and $C_2 =$ the capacity of the standard condenser $= 8{\cdot}43$ mμF), (3) $\theta$, (4) $\cos\theta$, (5) $C_1 = C_2 R_1 / R_2 \cos\theta$, where $R_2 = 54{\cdot}1$ ohms.

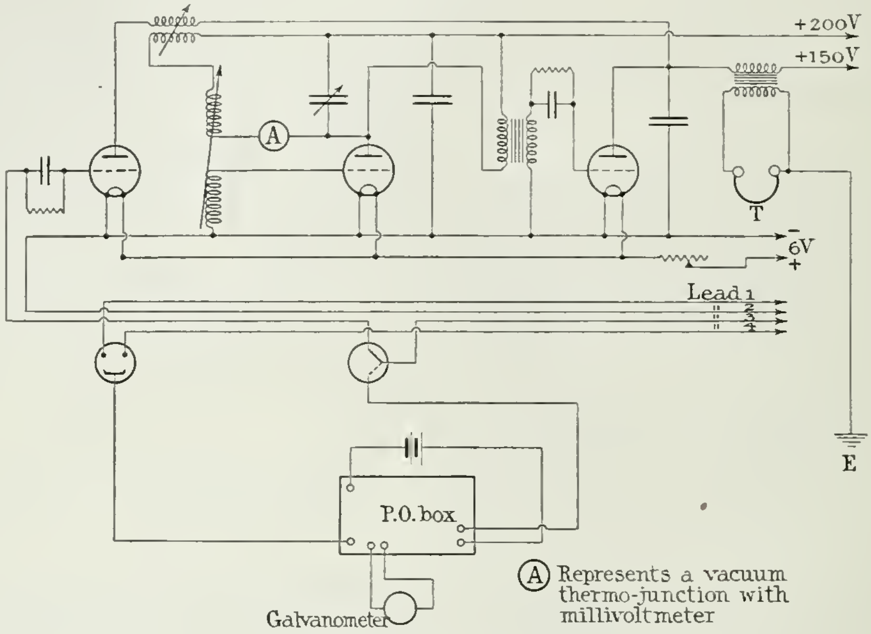


FIG. 2.—Detecting circuit.

The values of $\cos\theta$ so obtained were then plotted against $2\pi$ times the frequency (Fig. 5), and on the same sheet were plotted the values of $C_1$. Finally, curves were constructed of $\theta$ and $\sin\theta$ against $2\pi$ times the frequency (Fig. 6).

With regard to Figs. 3 and 4, the points marked X appear to be very scattered, but none shows a greater error from the value indicated by the curve than about 1 per cent in Fig. 3, and 3 per cent in Fig. 4.

In Fig. 5 the abscissæ were taken to indicate frequency instead of wave-length in order to facilitate extrapolation to direct-current conditions (i.e. frequency equals zero). The curve of $\cos\theta$ is the most important, as it indicates the results for which the research was primarily carried out, and it will be seen that the value of $\theta$ tends to zero at direct-current conditions and reaches the high value of about 30° at the highest frequency at which readings were taken. The value of $\cos\theta$ at audible frequencies is about $0{\cdot}995$, corresponding to results obtained in a previous calibration of these condensers.

Since $\theta$ has been taken as the complement of the angle between current and potential difference, $\sin\theta$ represents what is usually called the power factor of the condenser, and for this reason its values have been plotted.

The curve of $C_1$ (Fig. 5), however, is not so satisfactory. The values of $R_1$ have to be multiplied by the corresponding values of $\cos\theta$ to obtain those of $C_1$, and, although neither of the component curves has a point of inflexion, yet the resultant curve has such a point. Also, the alteration of the abscissæ from wave-length to frequency alters the order and character of the curve. Since, then, the points X are not sufficiently regular to allow the curves in Figs. 3 and 4 to be determined exactly, it follows that the shape of the $C_1$-frequency curve must be unreliable. It is, as a matter of fact, most unlikely that $C_1$ would rise and fall in the manner indicated by the points, and, for this reason, the curve has been plotted on a small vertical scale and the most probable curve drawn. The points obtained indicate, in the author's opinion, an undoubted tendency for $C_1$ to fall at high frequencies, and the curve has therefore been drawn to show this. A study of Figs. 3 and 4 at short wave-lengths also leads to this conclusion. The extrapolation of this curve to audible frequencies gives a value for $C_1$ which is 9·3 per cent higher than that obtained for this condenser in the earlier calibration referred to above.

The curve then of $C_1$ is generally unsatisfactory, but this does not, the author considers, invalidate the curves of $\theta$, and these, as pointed out above, are the results primarily required.

The accuracy of the results is difficult to determine. Care has been taken to exclude possible sources of error (e.g. capacity and inductance in the bridge wires), and the author would put the extreme limit of inaccuracy at ± 10 per cent. (It should be noted that this value includes the discrepancy in the audible-frequency value of $C_1$.) It is likely, however, that a more probable figure would be ± 5 per cent. In any case, with only one thorough test having been made (although this extended over several days), the value of the results obtained is not very great, but the author is of opinion that the general nature of the variation of the quantities is adequately shown.

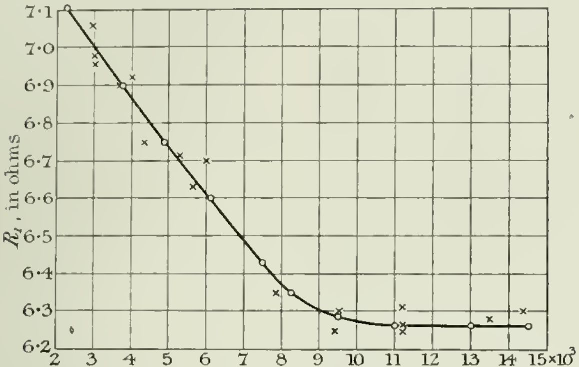


FIG. 3.

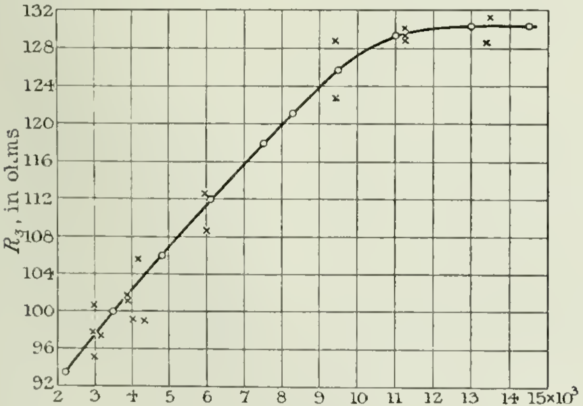


FIG. 4.

The drawback of the method is the actual physical difficulty of obtaining readings.*

The readings were taken under unfavourable conditions with regard to external noise. Not only mechanical but also electrical noises constituted serious sources of interference.

The following suggestions are offered for the purpose of facilitating future work of a similar nature:—

Cells should be used for all plate voltages. The largest possible air condenser that can be obtained should be used as a standard. This reduces the values of $R_3$ and will enable easier and more accurate determinations of that quantity to be made. The wires forming the resistances should also be as long as possible and as high as convenient from the ground. If both these conditions, i.e. large condenser and long wires, were realized, it would probably be convenient to use thicker wire for these resistances. As regards the sliding contacts for these wires, it is suggested that a small length (1 in. or less) of glass tube, filled with mercury, with a platinum wire sealed through

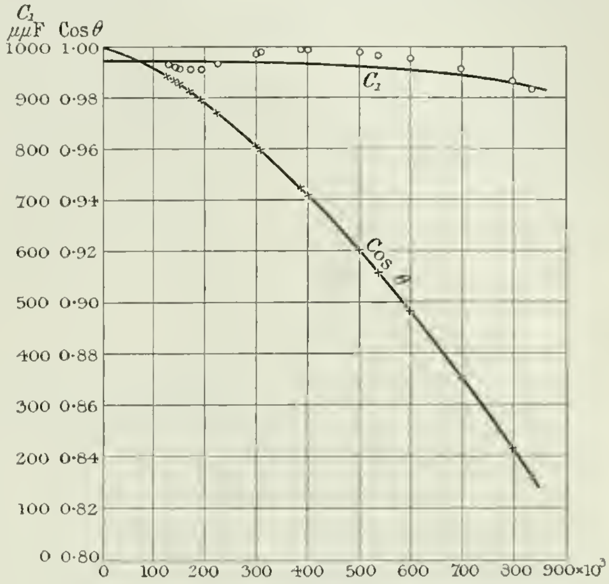


FIG. 5.

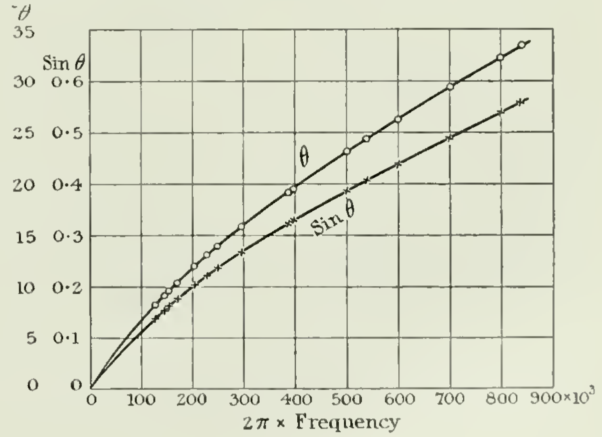


FIG. 6.

---

* Cf. J. A. FLEMING and G. B. DYKE, *Journal I.E.E.*, 1912, vol. 49, footnote to page 348.

the side, drawn out to capillary tubing each end and slipped over the Eureka wire, would solve all difficulties. The space between the capillary holes and the wire would of course be so small as to preclude all possibility of mercury leaking out.

In conclusion, the author would like to express his acknowledgment to Prof. G. W. O. Howe, D.Sc., for constant encouragement during the progress of this work.

### APPENDIX.

#### NOTE ON THE CONSTRUCTION OF THE CONDENSERS.

It may be of interest to observe that although the condensers used were constructed with stock laboratory materials, they proved capable of carrying a current of 7A at a frequency of about 500 000. They were of the ordinary type consisting of glass and tinfoil immersed in oil, and it is especially noteworthy that the tinfoil, previously damped with paraffin, was carefully squeezed on to the glass in order to prevent the formation of "blisters," which act as local condensers of small capacity and therefore of high impedance, ultimately causing the breakdown of the condenser. For the same reason, also, the tinfoil elements were duplicated and each pair separated by double sheets of blotting paper so as to ensure a perfect fit on both glass surfaces.

---

# PROCEEDINGS OF THE INSTITUTION.

## 27th MEETING OF THE WIRELESS SECTION, 7 FEBRUARY, 1923.

(Held in the Institution Lecture Theatre.)

**Professor C. L. Fortescue** took the chair, in the unavoidable absence of Dr. G. W. O. Howe, Chairman of the Section.

The minutes of the meeting of the Wireless Section held on the 10th January, 1923, were taken as read and were confirmed and signed.

A paper by Mr. J. Hollingworth, M.A., B.Sc., Associate Member, entitled "The Measurement of the Electric Intensity of Received Radio Signals" (see page 501), was read and discussed, and the meeting terminated at 7.55 p.m.

## 694th ORDINARY MEETING, 15 FEBRUARY, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 1st February, 1923, were taken as read and were confirmed and signed.

Professor J. T. MacGregor-Morris and Mr. G. Broughall were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows :—

### ELECTIONS.

*Member.*

Roffey, Myles Herbert, M.Sc.

*Associate Members.*

Aston, Kenneth, B.Sc. Tech.
de Lautour, Francis.
Douglas, John.
Macready, Henry John, B.Sc.
Moss, Arthur Edward.
Moullin, Eric Balliol, M.A.
Mutch, George, B.Sc.
Sainsbury, Graham Wilfred, B.Sc. (Eng.).
Shaw, William Albert.
Thomasson, James.

*Graduates.*

Brown, Robert Hartley C.
Chedzey, Ernest.
Dixon, Reginald Griffith.
Doel, Herbert Randolph.
Downes, Frederick Alan.
Fisher, Wilfred.
Fox, John Thomas.
Heath, George Frederick.
Lush, Reginald Vernon.
McAulay, Ernest, B.Sc.
Milner, Donovan Robert F.
North, Sydney Ernest.
Parton, Victor Gordon B.
Richardson, William Ernest.
Smith, Harry Foster.
Srinevasa Murthy, Ponnathapur.
Woodman, William.

*Students.*

Astley, Ronald.
Atta, Mohammed Aref A.
Avison, Robert Geoffrey.
Bainbridge, Stanley Rendle.
Baker, Claude Frederick G.
Baxter, Henry Wright.
Bellamy - Law, John William.
Bent, Fred.
Berry, Norman.
Beswetherick, Noel Ivor.
Booth, Fred.
Bowden, Peter McGregor.
Boyd, John Stephen.
Boyd, William.
Brooking, Colin Huntley.
Buckner, Henry Ray H.

*Students*—continued.

Butterfield, Leslie John.
Bygott, Hugh Cecil.
Cattaneo, Edward.
Chapman, Robert Frederick.
Cohen, Isaac Judah, B.Sc. (Eng.).
Collings, Henry Bernard.
Cooke, Maurice Wyndham.
Cooper, Eric Raymond.
Cooper, James Cuthbert.
Courtney, Thomas.
Couzens, Albert Harry.
Cowlishaw, Alwyn.
Cox, Stephen Seaford.
Creasser, William Birks.
Dawe, Frank Walter.
Douthwaite, Thomas.
Dudley, Edward Charles.
Eccles, Josiah, B.Sc.(Eng.).
Erskine, David Beveridge.
Fehr, Douglas.
Fletcher, Frederic Harold.
Fry, Cedric Edmund.
Gladstone, James William B., B.Sc.
Glenny, Arthur Philip.
Goode, Reginald Walter.
Guthrie, Robert.
Haigh, Daniel Grenfell.
Hamlyn, Arthur Macfarlane.
Hitchcock, Gerald Edward.
Hockin, Philip Richard P.
Hoit, Archibald William.
Hollis, Alfred Charles.
Holmes, William.
Hope, David Douglas W.
Hornby, John Reginald.
Horsfield, Eric Bee.
Hudson, Albert, B.Sc. (Eng.).
Hunt, Douglas Hawthorn.
Hurlbut, Francis John.
Jenkinson, Henry Gibson.
Jenvey, Frederick James.
Johnson, Stanley Charles.
Jones, John.
Kay, Charles McPherson.
Kearley, Norman Edwin.
Kemp, Alfred Norman.
Kemp, Walter Langley.
Kinghorn, David, B.Sc. (Eng.).
Kinsman, Albert Reginald.
Kirkby, John Martin.
Kirkby, Lionel John N.
Kitto, Francis Mansel.
Knott, Bernard.
Larnach, Robert.
Lloyd, Eric Martin.
Longworth, Frank.
Lord, Charles Lubben.
Luckman, Joseph Montague G.
McKenzie, Duncan Cadenhead.
Mann, John William A.
Matthey, Henry Albert.
Milne, William Hamilton.
Mitchell, Arthur Leslie.
Nash, William Lees.
Nightingale, Donald Alfred J., B.Sc. (Eng.).
Nicoll, Henry William.
Norwood, Herbert Harold.
Nurse, Arthur Philemon, Jun.
Nuttall, Branson.
O'Farrell, George Callender.
Palmer, Edward Barry.
Parker, Edward Howard.
Parkinson, George.
Perret, Louis Bryan.
Pinto, Cyril Alexander.
Pinto, Oscar Joseph.
Polgreen, Geoffrey Richard.
Quinton, Harold Frederick.
Rao, Channapatna Subba, B.E.
Reiss, Conrad.
Robertson, Philip White.
Robson, Oswald Leonard.
Ryder, Clifford.
Sadler, Ernest Henry.
Sahgal, Amarshand.
Schofield, Harry Ronald.
Scott, Gordon Irwin.
Semple, Leslie George.
Shepherd, Joseph Hubert.
Shishini, Mahmoud El.
Slater, William Hayton.
Slight, Charles Stanley B.
Smitherman, William Henry.
Speedy, Wilfred Henry.
Statham, Basil Fielding.
Stephens, Jack William S.
Stonehouse, Marshall Dale.

*Students*—continued.

Stott, John Chadwick.
Strachan, Andrew Anderson.
Sykes, Percy.
Taylor, Hugh Leake.
Teal, John Robert.
Terry, Victor John.
Theobald, Kenneth Leslie.
Thomson, Douglas Charles.
Thomson, George Gordon.
Thress, Leonard Archibald.
Trimen, Alfred Edwin.
Varcoe, Harold Hawkey.
Wade-Cooper, Frederick.
Walker, Allan Matthias.
Watson, Donald.
Watson, Thomas Hugh.
West, William, B.A.
White, Joseph John.
Whitehead, Fred.
Whitehurst, Arnold.
Whiteing, Albert Stanley.
Whittaker, Stanhope Clarence.
Whyman, Leslie Fieldhouse.
Wilmotte, Raymond Maurice.
Wilson, Edward Robert.
Wilson, Kenneth Ellerby.
Wyatt, Bernard Bullen, B.Sc.
Wykeham, William Aubrey P.

TRANSFERS.

*Associate Member to Member.*

Benham, Ernest Eustace.
Kidd, George Watson.
Kirk, George Lingard.
Lepine, Lionel John.
Mark-Seymour, Charles.

*Associate to Member.*

Mertens, John Thompson.

*Graduate to Associate Member.*

Freedman, Paul.
Jackson, Harry Yule V., M.C.
Jones, John Williams.
Lewis, Hubert John.
Moore, George Edward.
Williams, Vernon Eustace.

*Student to Associate Member.*

Hillman, Eric Rodney.
Rendle, Gerald Alfred, B.Sc.

*Student to Graduate.*

Birch, Robert Rule.
Birmingham, William.
Coulthard, William Barwise.
Dibben, Ernest.
Edwards, Leslie.
Fraser, Sidney Harold.
Hinton, Sydney.
Nuttall, Edgar Moorehouse.
Parkinson, Darwen.
Payne, Norman.
Scott, Thomas Robertson, B.Sc.(Eng.).
Vanneck, Richard Grant, M.C.
Wray, Francis D'Arcy.

The President announced that at the Council Meeting held that afternoon the second award of the Faraday Medal had been made to Sir Charles Parsons, K.C.B., F.R.S., Honorary Member.

A paper by Mr. J. Rosen, Member, entitled "Some Problems in High-Speed Alternators, and their Solution" (see page 439), was then read and discussed, and the meeting terminated at 7.56 p.m.

# BENEVOLENT FUND.

## 25th ANNUAL GENERAL MEETING, 31 MAY, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 5.45 p.m.

The Notice convening the meeting was taken as read.

The minutes of the 24th Annual General Meeting held on the 25th May, 1922, were taken as read and were confirmed and signed.

The Report of the Committee of Management (see below) and the Statement of Accounts for the year 1922 (see page 703) were presented and, on the motion of the Chairman, seconded by Mr. Ll. B. Atkinson, were unanimously adopted.

On the motion of Capt. R. J. Wallis-Jones it was unanimously resolved that Mr. J. Attfield, F.C.A., be elected Honorary Auditor for the year 1923–24.

The Chairman reported that under Rule 10 the Council had appointed the following Committee of Management for the year 1923–24 :—

The President (*ex-officio*).

| | |
|---|---|
| Mr. S. Evershed<br>Mr. P. V. Hunter, C.B.E.<br>Lieut.-Col. F. A. Cortez Leigh, T.D., R.E.<br>Sir A. M. J. Ogilvie, K.B.E., C.B.<br>Dr. A. Russell<br>Mr. A. A. Campbell Swinton, F.R.S. | Representing the Council ; |
| Mr. J. R. Cowie<br>Mr. J. E. Kingsbury<br>Mr. P. Rosling | Representing the Contributors ; |

and the Chairman of each Local Centre in the United Kingdom.

The meeting then terminated.

## REPORT OF THE COMMITTEE OF MANAGEMENT FOR THE YEAR 1922.

### Capital.

The Capital Account stood on 31st December, 1922, at £9 969 11s. 3d., all of which is invested.

### Receipts.

The Income for 1922 from dividends, interest and annual subscriptions was as follows :—

| | £ | s. | d. |
|---|---|---|---|
| Dividends on investments .. .. | 391 | 10 | 11 |
| Interest .. .. .. .. .. | 23 | 2 | 9 |
| 303 annual subscriptions .. .. | 231 | 4 | 6 |
| | £645 | 18 | 2 |

In addition to the foregoing, the Fund benefited during the year as follows :—

*Ordinary Donations :*

| | £ | s. | d. |
|---|---|---|---|
| Electrical Engineers' Ball Committee .. | 57 | 15 | 0 |
| Informal Meetings Committee .. .. | 25 | 0 | 0 |
| Midland Electrical Engineers' Ball Committee .. .. .. .. | 20 | 0 | 0 |
| W. T. Henley's Telegraph Works Co., Ltd. .. .. .. .. .. | 15 | 15 | 0 |
| C. S. Franklin .. .. .. .. | 10 | 0 | 0 |
| J. D. Dallas .. .. .. .. | 10 | 0 | 0 |
| F. R. Marsh .. .. .. .. | 10 | 0 | 0 |
| and 669 non-recurring donations of under £5 .. .. .. .. .. | 252 | 7 | 0 |
| | £400 | 17 | 0 |

*Special Donations :*

(Sir E. M. Hughman's appeal) .. £1 767 11 10

The balance of the Income and Expenditure Account amounted on 31st December, 1922, to £1 463 1s. 3d., of which £1 002 19s. 3d. was invested, and £275 on deposit with the Institution bankers.

### Donors and Subscribers.

Lists of the names of donors and subscribers during 1922 have been published in the *Journal.*

The Committee of Management desire to acknowledge their indebtedness to the donors and subscribers, and they venture to urge upon members the pressing need for a generous support of the Fund. Apart from donations, the Committee will be grateful for annual subscriptions even of small amounts.

### Grants.

Applications for assistance were made by or on behalf of 17 persons during 1922, and the Committee, after due consideration, made grants in 16 of the cases. One grant was made of £123, one of £79, one of £65, one of £63, one of £61, five of £50, one of £35, two of £30, one of £20 5s., and two of £10, a total of £776 5s.

### Wilde Fund.

The Capital Account stood on the 31st December, 1922, at £2 798 10s. 2d., the whole of which is invested and brings in an annual income of £99 12s. 5d.

The balance standing to the credit of the Income Account, from which, under the Trust Deed, full Members only can benefit, on the same date was £79 15s. 5d.

No grant from this Fund was made during the year.

# THE BENEVOLENT FUND OF THE INSTITUTION OF ELECTRICAL ENGINEERS.

## INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR 1922.

**Dr.** EXPENDITURE.

| | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|
| To Grants ... ... ... ... ... ... ... ... ... | | | | 776 | 5 | 0 |
| ,, Printing, Stationery, Bank Charges, Postage, etc. ... ... ... | | | | 48 | 13 | 6 |
| ,, Unexpended Balance carried to Balance Sheet ... ... ... | | | | 1,989 | 8 | 6 |
| | | | | £ 2,814 | 7 | 0 |

INCOME. **Cr.**

| | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|
| By Dividends on Investments... ... ... ... ... ... ... | | | | 391 | 10 | 11 |
| ,, Interest ... ... ... ... ... ... ... ... ... | | | | 23 | 2 | 9 |
| ,, Annual Subscriptions ... ... ... ... ... ... ... | | | | 231 | 4 | 6 |
| ,, Donations of £5 and over ... ... ... ... ... ... ... | | | | 148 | 10 | 0 |
| ,, Donations under £5 ... ... ... ... ... ... ... | | | | 252 | 7 | 0 |
| ,, Special Appeal in connection with offer of Sir E. M. Hughman (late of Bombay) :— | | | | | | |
| Donations ... ... ... ... ... ... | £1,762 | 5 | 4 | | | |
| Annual Subscriptions ... ... ... ... | 5 | 6 | 6 | | | |
| | | | | 1,767 | 11 | 10 |
| | | | | £2,814 | 7 | 0 |

## BALANCE SHEET, 31ST DECEMBER, 1922.

**Dr.** LIABILITIES.

| | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|
| To Capital Account :— | | | | | | |
| As per last Balance Sheet ... ... ... ... | £7,859 | 7 | 3 | | | |
| Amount transferred from Income in 1922 ... | 2,110 | 4 | 0 | | | |
| | | | | 9,969 | 11 | 3 |
| ,, Income and Expenditure Account :— | | | | | | |
| As per last Balance Sheet ... ... .. ... | £1,583 | 16 | 9 | | | |
| Unexpended Balance in 1922 ... ... ... ... | 1,989 | 8 | 6 | | | |
| | 3,573 | 5 | 3 | | | |
| *Less* Amount transferred to Capital in 1922 ... ... | 2,110 | 4 | 0 | | | |
| | | | | 1,463 | 1 | 3 |
| ,, Sundry Creditors ... ... ... ... ... ... ... ... | | | | 21 | 10 | 0 |
| | | | | £11,454 | 2 | 6 |

ASSETS. **Cr.**

| | £ | s. | d. | £ | s. | d. |
|---|---|---|---|---|---|---|
| By Investments (Capital), at cost :— | | | | | | |
| £961 7s. 7d. Cape of Good Hope 3 % Stock ... ... ... ... | | | | 950 | 0 | 0 |
| £593 1s. 7d. New South Wales 3 % Stock ... ... ... ... | | | | 600 | 0 | 0 |
| £420 Great Eastern Railway 4 % Preference Stock ... ... | | | | 503 | 18 | 3 |
| £600 North Staffordshire Railway 3 % Debenture Stock ... ... | | | | 551 | 0 | 9 |
| £750 East Indian Railway 3½ % Debenture Stock ... ... ... | | | | 737 | 18 | 0 |
| £300 London and North-Western Railway 4 % Guaranteed Stock | | | | 333 | 11 | 6 |
| £500 New Zealand 3½ % Stock ... ... ... ... ... ... | | | | 486 | 18 | 6 |
| £500 Canada 3½ % Stock ... ... ... ... ... ... | | | | 478 | 16 | 0 |
| £1,126 6s. 3d. 5 % War Stock ... ... ... ... ... ... | | | | 1,067 | 6 | 6 |
| £350 New South Wales 4 % Stock ... ... ... ... ... | | | | 336 | 18 | 6 |
| £200 3½ % War Stock ... ... ... ... ... ... ... | | | | 188 | 17 | 3 |
| £2,128 8s. 6d. 4 % Funding Loan ... ... ... ... ... | | | | 1,624 | 2 | 0 |
| £2,000 5 % National War Bonds ... ... ... ... ... | | | | 2,110 | 4 | 0 |
| | | | | 9,969 | 11 | 3 |
| ,, Investment (Income) at cost :— | | | | | | |
| £1,000 5 % War Stock ... ... ... ... ... ... ... | | | | 1,002 | 19 | 3 |
| ,, Sundry Debtors ... ... ... ... ... ... ... ... | | | | 8 | 3 | 3 |
| ,, Cash :— | | | | | | |
| At Bankers' ... ... ... ... ... ... | £442 | 9 | 1 | | | |
| In hand ... ... ... ... ... ... ... | 30 | 19 | 8 | | | |
| | | | | 473 | 8 | 9 |
| | | | | £11,454 | 2 | 6 |

I have audited the above Balance Sheet and Income and Expenditure Account with the Books and Vouchers and certify them to be correct, and have verified the Investments with Certificates from Bankers. The Investments, which are stated at cost, are subject to depreciation.

JAS. ATTFIELD, F.C.A.
*Honorary Auditor.*

*16th May*, 1923.

# DISCUSSION ON

## "THE MAINTENANCE OF VOLTAGE ON A D.C. DISTRIBUTION SYSTEM BY MEANS OF A FULLY AUTOMATIC SUBSTATION."*

NORTH-WESTERN CENTRE, AT MANCHESTER, 20 FEBRUARY, 1923.

**Mr. B. Welbourn:** I have already taken part in the discussion on this paper (see page 425), but as the President in closing the London discussion asked for information in regard to semi-automatic substations I think that it should be put on record that 31 years ago semi-automatic substations were designed, manufactured and put into regular operation by British engineers on two-wire systems in this country, particularly at Windsor, Oxford, Hull and Wolverhampton. In those cases the substations were started up from a distance, and the indications of voltage were given through pilot wires. Plants were run up to speed and then they automatically switched themselves on to the busbars when the correct voltage had been attained.

**Mr. L. C. Benton:** On page 421 the author states that the automatic equipment has surpassed expectations in its performance, and also that it has dealt with artificial faults almost uncannily. This is only to be expected, as the operations follow in exactly the same order as those ordinarily performed by an attendant, the gear being so arranged that each step is simply the logical sequence of the previous one. There is no hesitation, and the whole operation is completed in considerably less time than a man could possibly do it. Judging from the discussions at other Centres very little criticism has been raised as to automatic substations being an engineering or commercial proposition. The points at issue appear to be questions as to the extent to which automatic control can be applied, and the best method of application. Each proposition that arises must be considered on its own merits; there is no hard and fast rule to apply to every scheme. The first essential is reliability, and that depends upon simplicity. At the first glance the equipment may seem to be somewhat lacking in simplicity. Really, however, it is not as complicated as it sounds when described in detail. One may imagine the whole operation going through in a few stages which take place more quickly than they can be stated. To begin with, the d.c. system indicates by falling voltage that more power is required. The apparatus, provided that a suitable three-phase supply of correct voltage is available, and that there is no fault existent in the equipment, causes a master relay to be energized which in turn closes the control circuit. That is the first step. Then follows the closing of the main oil switch, the starting of the machine, running it up to speed, correcting polarity if required, and connecting the machine on to the full voltage of its transformer. The next step is closing the machine on to the d.c. bars. It is then ready to deal with load immediately. On page 423 the numbers attached to the list of items comprising the equipment may tend to give a wrong impression. Considerably fewer than 64 pieces of apparatus are needed, more than half of them being of the simple, robust contactor type, which has proved its reliability in electric train service. Only the remainder consist of relays as ordinarily understood. Half of these take an active part in the functioning of the equipment; the others are solely for its protection. The protective features may seem numerous, but reductions must be made with caution as the present degree of protection is, after all, the result of a long period of development abroad, in which elimination has been effected as far as consistent with complete protection. It is of interest to note the distinction between the lock-out relay and the other forms of protective devices which merely shut the station down until the trouble is removed, when it automatically starts up again. The lock-out relay permanently closes down the substation until released by an attendant. It is important to note that in every case the relays operate by closing their contacts. Perhaps a little explanation of the auxiliary relay may be of value. The author simply states that it comes between the d.c. line contactor and the contactor for cutting out the limiting resistance. It is better considered as an interlock preventing the possibility of the latter contactor being closed before the line contactor and only permitting it to close if the current taken from the machine is not excessive.

**Mr. H. A. Ratcliff:** The subject of automatic substation plant has, so far, received very little attention in this country, no doubt because of the innate conservatism of British engineers. Automatic equipments have already made considerable headway in the United States, possibly to some extent because of labour conditions, but also, I think, because American engineers attach more importance to the development of imagination. The essential fact is that in this country at the present time there are in existence many large and important d.c. supply systems, and on economic grounds alone, quite apart from other considerations, the natural growth and development of such systems necessitate the employment of substations and high-tension a.c. feeders. In many cases in the earlier stages of development the substations are comparatively small; consequently the cost of the operators or attendants is relatively high, and from the men's point of view the job of attendant in a small substation is one of the most monotonous and ambition-destroying ones it is possible to have. For these reasons I think there is a very big field for completely automatic and semi-automatic equipments. Apart from public supply systems it is obvious that automatic equipments are eminently suitable for traction supplies, and I think they will also go a long way towards solving some of the problems in connection with railway electrification. The outstanding feature of automatic control is that the several operations may be performed in the correct sequence, or not at all, whereas the manual operator may perform them in the correct sequence, or in many incorrect ways, each of which may lead to more serious results than if he had not functioned at all. With regard to the matter of cost, I am satisfied that there is a good case to be made out for automatic equipments in their proper sphere, but I do not attach much importance to the figures given in the paper, because it is not possible to generalize from any one particular case and also because it must not be overlooked that at the present time the cost of automatic equipments is purely artificial. It is only natural that it should be so, but I quite expect that in a very short time costs will be only a fraction of their present values. That, of course, will have a very great bearing upon the relative cost of manually and automatically operated substations. It should then be possible to establish a good case for the employment of automatic equipments for dealing with the comparatively light night-load in large and relatively important substations on city networks, when it is either impossible or undesirable to link up the several sections during the light-load hours. Ultimately, no doubt, the provision of the automatic control gear, as distinct from the machines, will become a matter for the switchgear manufacturers, and in this connection I consider that the respective controls of machines and feeders should be kept as separate and distinct as possible. It may be said that all these complications can be avoided with an a.c. system of distribution, and perhaps to some extent that is true, but it must not be overlooked that many large d.c. systems already exist, and they possess certain very marked advantages. The regulation of a well-laid-out d.c. system is, comparatively speaking, very good, and furthermore, if the supply is from a main a.c. station, via high-tension a.c. feeders and converting plant in substations, it is possible to maintain a very good power factor at the generating station, whereas with an a.c. system of distribution the power factor may be low, in which case the regulation will certainly be bad unless comparatively expensive induction regulators are employed. In this connection there is obviously a field for automatically controlled a.c. substations, equipped with automatically operated induction regulators. Apart from these considerations the real advantages of an a.c. distribution system are extreme flexibility and the entire absence of osmotic troubles on the cables. The author will perhaps explain what is the essential difference between a manually operated station and an automatically operated station which necessitates the use of load-limiting resistances in the feeder circuits. They are never employed in a manually operated station, and, moreover, the pressure-drop is so great with resistances in circuit that the effective pressure on the network is too low to be of any use for lighting purposes, and therefore the feeders might as well be switched out entirely. On page 417 there is a reference to a very marked increase of load from about ½ kW to 1 kW in the case of lighting only, up to 5 or 6 kW in the case of a combined domestic load. That is, of course, the average increase per consumer, and I presume the author does not imply that the total effective increase on the network is in the same proportion. It is usually recognized that the diversity factor of the domestic load is very high. The automatic raising of the brushes when starting up the machines appears to be rather a crude arrangement, and it would be interesting to know whether it has given any trouble. On page 421, par. 5, the author says: " Naturally, numerous adjustments to the relays, etc., have been necessary." Why " naturally," and what was the nature of those adjustments? The paper deals entirely with a fully automatic equipment, but I consider that there is also a very good field for semi-automatic, or perhaps it would be more correct to say " remotely controlled," substations. Such stations would be linked up by a system of pilot cables to a centrally situated manual controller, and, further, it should be possible to combine the control with a suitable telephone system so that to a large extent the conditions prevailing in the several stations would be automatically signalled to the controller.

---

* Paper by Mr. P. J. Robinson (see page 417).

**Mr. G. F. Sills**: Speaking to an engineer interested in automatic substations for South America, I said that I thought the main reason—at any rate at that time—why one should go in for automatic substations was the costliness of labour, but as labour in South America was very cheap why was it necessary to install them there? His view was that if there was anything like serious trouble the operators cleared out in any case, and that it was better to have an automatic substation where there is a good chance of the automatic gear protecting the machinery. It is better to protect too fully rather than not sufficiently until we have acquired the necessary experience as to what can be left out. I should like to ask the author how many times a day the station comes into operation. One of the main features in the description which interested me was the fact that the rotary converter is tap-started, but has the complication of an auxiliary motor for raising and then lowering the brushes. This automatic feature has to be carried out through relays, and it would be interesting to know the number of relays that could be dispensed with if there were no necessity to raise the brushes. These extra relays, no doubt, complicate the other relays to some extent due to the time element. With rotary converters of the small size described by the author, viz. 500 kW, there seems to be no objection to tap-starting without the use of the brush-lifting device, as some modern rotary converters, in which the weight of the armatures is about 3½ times that in the case of 500-kW machines, are giving every satisfaction with that arrangement. It must be borne in mind, however, that the converter must be specially designed for this purpose. It is quite another matter to expect the ordinary design of rotary converter to be successful with a tap start, as a pony motor is usually necessary in such cases.

**Mr. G. A. Juhlin**: I think that the author is to be congratulated on the method adopted for solving a difficult operation problem. It is only through operating engineers being willing to adopt new plants of this kind that progress can be made. It should be pointed out that, while such apparatus is new to this country, yet a great deal of experience is behind its development. Much credit is due to American engineers, as both the Westinghouse and the General Electric Companies of America have a considerable number of automatic stations operating satisfactorily. Naturally, experience has not been gained without a considerable amount of trouble in the initial stages, and it is reasonable to expect that anyone entering this field without having the advantage of past experience will have to pass through similar troubles. There is, of course, no reason to assume that such troubles will not be overcome in time, but it undoubtedly means inconvenience to operating engineers during the experimental period. It has been suggested that it would be advantageous if the automatic portion of the gear were supplied separately in the same way as ordinary switchgear is supplied. Suggestions have been made, also, that simplicity would be attained by starting without lifting the brushes. In smaller sizes there is no difficulty whatever in starting without brush-lifting gear, but for larger sizes the wear and tear on the brushes is heavy, and I suggest that such gear is a good investment from the point of view of keeping down maintenance cost in brushes. I think that considerable developments may undoubtedly be expected in this class of apparatus, not only so far as substations are concerned but in automatic a.c. plant generally.

**Mr. G. G. L. Preece** : Under the particular conditions specified I think that the author was fully justified in putting in his automatic set, but if he had sufficient faith in the machines to let them run unattended I wonder whether he would still put in such sets. In this country there are a considerable number of public supply substations where the converters are left unattended after being started up in the morning until shut down at night. One man goes round early in the morning to start up. He may deal with two, three or more substations, and it is therefore necessary to get the stations running some little time before the load comes on, but then they are left absolutely unattended. They are all shut down at night by one man. There are a good many industrial converters which are operated in practically the same way. Of course, all these substations of which I am speaking operate on lighting and power loads. Attendants are required at substations operating on a traction load, unless automatic features are introduced. The author states that the substation described operates occasionally on traction load when traffic is dense. On occasion, therefore, attendants would have been necessary had he adopted a substation normally running unattended. I wonder whether the author will have a man in any case at his automatic substation on "Grand National" day. I have seen many automatic devices in use on other branches of power station work. They offer perhaps the most effective way of dealing with the particular problem, but sometimes they are installed without any regard to the capital cost. I know one or two places where such automatic devices have worked quite well, but when considered from a business point of view it has been found cheaper to operate manually. This particular feature will have to be considered very carefully, especially in the case of small and medium-sized power stations. If the engineers of the latter have such faith in converting plant as to run it unattended, with manual starting and stopping, it becomes a moot point whether they are justified in putting in automatic gear. As regards semi-automatic converting plant, there are examples now in use, particularly in Hull. There they have the advantage of pilot cables laid down for the automatic control of their old system of high-tension d.c. substations, and they are taking advantage of these for their newer converting plant. Their scheme is a good deal cheaper than fully automatic stations at present prices. It is difficult to say now whether fully automatic stations could be put down more economically, but prices should certainly fall after experience has been gained. It must not be thought that I am deprecating automatic substations; under many conditions they are suitable. I am personally very interested in the Reyrolle-Peebles system, and before long an opportunity will arise in Manchester of comparing three different systems of completely automatic substations, namely the Metropolitan-Vickers as described in the paper, the British Thomson-Houston, and the Reyrolle-Peebles; the last-mentioned should be interesting to those who correctly spoke of the problem as being one for the switchgear manufacturer.

**Mr. H. C. Lamb** : The author has made out a very good case, financially, for the automatic substation. There are, of course, some advantages, quite well known to him, which it is neither usual nor advisable to mention publicly. Four automatic substations should be running in Manchester before the end of the year, and as they will be of different designs we hope to get some interesting comparisons which should result in the greater simplicity asked for in this discussion. The author refers to feeders in Liverpool of unequal length, and states that many of the long feeders were running at only 30 per cent of their full carrying capacity, but is it not usual, where feeders running out from one substation are of unequal length, to work the long feeders at a higher busbar pressure than the short ones, thus obtaining the full duty from them? In the paper there is little information about the cable lay-out, but the author has amplified it to-night. I think he said that the new substation was rather less than a mile from one of the existing substations, and that the cables to be turned into the new substation were two 0·3 in. feeders. On page 422 the cost of the cable from the existing substation to the point where the automatic substation is located is given as £12 500. It would appear that a feeder might be run out from the nearest existing substation to the new feeding point, large enough to supply two 0·3 in. distributing cables, at about half the cost given in the paper. Also, in alternative (4), where the author makes the comparison between the manually operated and the automatic substation, he states that three shifts (of two men per shift) would be required, costing £1 285 per annum. As the substation is only running 12 hours a day, I should have thought it could be worked by two men instead of six and that the cost would be under £400 per annum. The cost of lighting is given as £20, but it should be only about one-quarter of that amount.

**Mr. J. H. Williams** : Recorders are now being fitted to automatic substations to record the operations of the various relays and to record when they fail. Mr. Juhlin referred to automatic equipment in the United

States. The General Electric Co. of America have about 200 already running in that country. The first one was described in the *Electrical World* (1913, vol. 61, p. 1422). There are several now being built in this country in addition to that at Liverpool, including twelve 3 000-volt three-phase 50-period substations controlling 22 motor-generators of 2 000 kW capacity each. Some of these substations contain three machines. With regard to three-wire stations there are, I believe, at least 15 sets now running in the United States, i.e. 10 for the Kansas City Light and Power Co., and 5 for the Detroit Edison Co.

**Mr. G. A. Cheetham:** I have not much to add to what I have already said in London on this subject (see page 426). There is one point that has been mentioned on several occasions, namely, a doubt regarding the efficacy of the field-reversing arrangement. It has been suggested that on occasions the latter does not work. This suggestion is incorrect. When reversing the field the American Westinghouse Co. did not originally split the field into two halves and connect them in parallel. That modification proved to be a complete solution of the trouble they had in reversing polarity in one or two early cases. A point which has not been mentioned to-night is the development of automatic equipment for controlling hydro-electric stations. This is well advanced now in the United States and will no doubt be adopted in Europe. Strange to say, it is very much simpler than the control of a rotary-converter station, and there is no doubt a very large field for development. I gave during the London discussion an extract from a report from one of the American engineering associations on the result of their experience of the performance of automatically operated stations. Their verdict was that from the operating records there was no doubt that automatically operated stations were more reliable than manually operated stations, and that after a shut-down the restoration of the voltage was very much more rapid with automatic control.

**Mr. E. Thomas:** It is an outstanding fact that this paper is presented by a purchaser who expressed himself as highly satisfied. It was well-known previously that many automatic substations were in use already in America, but it was not known whether the results obtainable would be satisfactory to the engineer of a large English municipal supply organization for lighting and power purposes. The chief questions now are whether the substation will continue to operate without an undue number of failures and without undue maintenance cost; and under what conditions it should or should not be used. In regard to the first point, viz. reliability without undue maintenance, we are depending upon great numbers of relays and contactors with almost hundreds of contacts, many of them necessarily delicate. There is already a cry for reduction in cost, and the pressure in this direction brought to bear on designers will be very severe, and it is important that the utmost vigilance be maintained in the future in order that improvement and not deterioration shall take place in the robustness and reliability of the separate details. It is to be remembered also that only a single set has been installed. If several sets are to be installed in one substation, then further gear will be necessary for selection purposes. Then, too, in most large supplies the load comes on very rapidly at certain hours. In Manchester, for example, there is probably a sudden increase at 7.55 a.m. as so many works start at that time. It would probably be undesirable to have many sets starting up together, lest the a.c. supply voltage were affected, and hence some anticipating gear or time switches might be required in addition. Amongst the alternatives which the author considered before deciding on the automatic substation, he does not mention the semi-automatic, to which Mr. Preece has already referred. In many cases this will be considered to be a very desirable proposition. It has been in use in Hull for over 25 years and has satisfied the engineer so well that he now considers it the obvious and desirable plan to follow. His substations, like fully automatic substations, are normally locked up and left to themselves. By means of a small number of pilot wires any set can be started up, synchronized and paralleled on to the bars from an operating room at the generating station. The voltage can be regulated and the load taken by each machine can be seen; indeed, one can have a sort of bird's-eye view of the whole system. Further, sudden load requirements can be anticipated. Finally, in case of a complete shut-down of any section of the network—a matter of some dread to every supply engineer—a number of sets can be started up and got running, and all connected simultaneously on to the d.c. bars by the operation of a single, small, control switch. In the semi-automatic station much of what happens is automatic as in the fully automatic substation. Up to now we have perhaps doubted whether automatic operation could be as efficient and reliable as hand operation. I venture to predict that before long this attitude will be reversed. Within the last few weeks the authorities have announced their intention of installing automatic telephones throughout the country. Automatic operation has become so efficient and reliable through development that it is now regarded as being much quicker and more satisfactory than manual operation. The author already compares his substation favourably in this respect with manually operated plant, and in the future, in its automatic or semi-automatic form, it will doubtless be regarded as indispensable to modern standards of operating efficiency and as being necessary apart from considerations of cost. Any doubts as to the safety of leaving suitable automatic or semi-automatic plant running unattended, even without all the innumerable safety devices described in this paper, will be dispelled by consideration of the Hull supply system, where this has been the practice for over 25 years and where the practice is now in actual process of energetic development.

**Mr. A. B. Mallinson:** From the author's lucid description I see that everything is done automatically until one comes to the oil circuit-breaker (20); I should like to know why a mechanical latch was put on that. These systems are going to be of great importance to the large supply corporations which have a d.c. distribution network with alternating current superimposed. But it is necessary to consider also the great number of installations in this country which have no a.c. supply. If they are to participate in the benefits they must put in an a.c. system as a preliminary step. It seems to me that there will be a field for the class of small substation where, instead of having a rotary converter, one has a Diesel or semi-Diesel set or a small water supply, which will automatically be switched in and will enable those who do not possess an a.c. feeder system to minimize transmission losses and to obtain a much larger supply out of their existing cables. I think that we can look to the engine makers to provide engines to start automatically, run without a man standing by (as the small house-lighting plants operate), and cut out if anything goes wrong.

**Mr. E. P. Hill:** The difficulty with automatic equipment seems to be the selection of apparatus which, while being reliable, shall be able to perform all the functions necessary, and shall also be a commercial proposition, i.e. not too expensive to manufacture. In this connection I should like to speak of one or two items included in the automatic equipment. The first is the brush-lifting gear, which is not always necessary. Certainly on, say, a 250 kW rotary converter the brush-lifting gear would not be necessary, and consequently relatively less expensive and simpler connections would be suitable. Again, on 25-period sets of even 500 kW capacity it would not be absolutely necessary. The operation of raising and lowering the carbons keeps them free in the holders and helps commutation, which is a point in favour of brush-lifting gear. Tap-starting is the simplest and generally most reliable method of starting small and medium-sized sets, but it does necessitate that the polarity on the d.c. side shall be determined definitely before the converter is ready for load, and, as described in the paper, a polarity relay is usually provided to take care of this, as there is no certainty that the machine will pull into step with correct polarity. This polarity relay is a sound proposition but somewhat expensive. The following method recently patented by the Metropolitan-Vickers Company,* as an alternative to the polarity relay, although successful on works tests has not yet been tried in service. A Wheatstone bridge of Nodon valves is arranged so that the field is connected across the centre points. The outers are connected to the d.c. brushes which are pulsating during the starting period at a voltage depending on the slip of the rotary armature. The valves are so connected as to apply field current of correct polarity to the rotary field from the moment of starting (or later, as desired), and suitable switchgear cuts out the valves when the converter has pulled into step. It was found possible to allow the machine to build up with wrong polarity without valves, and to correct it immediately on inserting the valves. As these are only in circuit for a few seconds they can be made very cheaply, and virtually they take the place of separate excitation.

**Mr. J. Frith:** I should like to mention the fully-automatic private lighting plant. The fact that this is very much smaller than the plant under discussion to-night does not make its problem any easier but rather much more difficult, because when one is spending thousands on the plant one can afford to make the automatic part on sound engineering lines, but when the whole job has to be done for a few pounds it is naturally more difficult. The first of these plants I handled more than 10 years ago, and it is still working; since then I have put in several others. They start automatically from either of two causes; either the load is too great for the battery to deal with alone, or the battery requires charging. Having started they automatically maintain constant voltage on the feeders, switching cells in and out, shutting down when either the battery is fully charged or the load drops to a predetermined value. As is the case with the larger plant described this evening, these smaller plants exercise a good deal of discretion; for instance, if after having been motored for a certain time the engine fails to start, then the conclusion is adopted that the petrol tank is empty, and the plant is locked out till the attendant supplies what is necessary. Throughout this discussion these automatic substations have been referred to as new. Credit should, I think, be given to these small plants which have been operating for a number of years and which are quite as wonderful in their way as the fully automatic substations. I should like to confirm what has been said as to one great advantage of the paper, in that it is the purchaser and user who has come forward to tell us about a new departure from his point of view.

**Mr. A. S. Barnard:** I was the engineer responsible for putting down the Oxford system in Hull where we had, I think, well over a dozen substations, all controlled from the generating station by pilot wires. At all those substations the plant was run without any attention beyond what was given by a man patrolling the town on a bicycle. The failure—if it is a failure—of the Oxford system in various towns in this country is not due to the plant being run without constant attention, nor is it due to any inefficiency of the semi-automatic switches in the substation, which were controlled by pilot wires from the generating station. It is owing to inherent defects that the system has fallen out of use, and certainly not because the machines could not be trusted to run without attention, nor because the automatic apparatus was unreliable.

**Mr. P. J. Robinson** (*in reply*): In reply to Mr. Ratcliff, I would point out that the limiting resistances are not in the feeder circuits, but are between the converter and the feeder bars, and are, of course, out of circuit when the converter is not operating, while the feeders are still alive from an external source, and feeder contactors are kept closed quite independently of the converter automatic gear. As explained elsewhere, the increase to 5 or 6 kW does not imply a total effective increase, due to the diversity factor being high. The brush-raising gear is quite satisfactory and, far from being crude, is rather a clever device. I am rather surprised that Mr. Ratcliff should ask why adjustments should be necessary, as in practice very little plant is operated without some adjustment and it is these minor adjustments that are referred to in the paper.

In reply to Mr. Sills, the station comes into operation, normally, in the winter months twice a day, and at other times only once.

---

* British patent specification, 18 815, Metropolitan-Vickers Electrical Company and E. P. Hill.

Mr. Preece asks if a man is in attendance on days of heavy traction load. This is so, for it would obviously not pay to put in automatic gear for these rare occasions. As regards leaving operating plant unattended, it would appear that in case of trouble on the high-tension line all these stations would shut down and remain shut down until an attendant was able to get round to start them again, a considerable period elapsing before all were in operation once more. Mr. Preece remarks that the Reyrolle-Peebles system should be interesting to those who correctly spoke of the problem as one for the switchgear manufacturer. Why should he say Reyrolle-Peebles ? The Metropolitan-Vickers Co. and the British Thomson-Houston Co. also make very satisfactory switchgear.

Replying to Mr. Lamb, I agree that there are some advantages which it is not desirable to discuss publicly. I note that there will soon be four automatic substations in his area, and no doubt he will be in a position at an early date to discuss the relative merits of different types of automatically controlled stations. With regard to his statement of feeders being of unequal length, I cannot find any place in the paper in which I make this statement. In the case in question, the feeders are comparatively short and the distributors are long ; the question of boosting is therefore out of the question. The cables that we turned into the station were four 0·3, 0·2, 0·3 sq. in. distributors. The estimate of £12 500 given in the paper is for cables that would be required to feed into the system at the same point as the automatic station is now feeding. The turning-in of the distributors has given us an effective area of 1·2 sq. in. of copper on each pole, and I cannot agree that a feeder to carry 1 200 amperes and to maintain the full voltage at this point can compare with the arrangement which we have adopted.

The information given by Mr. Williams is very interesting, and the relay-operation recorders should be a great help in determining the point of failure, should occasion arise.

In reply to Mr. Thomas, I do not think that automatic stations would give any trouble due to many sets starting together, as it is obvious that the load has to be picked up at the time stated, and the fact that it is an automatic station is immaterial. Many speakers in suggesting semi-automatic stations have lost sight of the fact that no pilot wires existed in the case mentioned. The laying of these would very materially have affected the first cost, and probably the fully automatic station would be cheaper in the end.

Mr. Mallinson calls attention to the mechanical latch on the oil circuit-breaker. All electrically operated oil switches which have come to my notice have a mechanical latch, and there appears to be no object in departing from that practice in the present instance.

Mr. Hill comments on tap-started rotary converters, but, as stated elsewhere, this is outside the scope of the paper.

I fully appreciate that small battery-charging gear has been operated automatically for some years, and I thank Mr. Frith for his information regarding them.

Referring to Mr. Barnard's remarks, it would have been of interest to hear what were the inherent defects in the Oxford system at Hull, and why these defects could not be corrected.

## SCOTTISH CENTRE, AT EDINBURGH, 13 MARCH, 1923.

**Mr. R. B. Mitchell :** I fully agree with the idea that the question of running long and heavy d.c. feeders to fulfil the obligations of any undertaking is quite out of count nowadays when compared with the cost of putting down a substation—quite a small one—at the mid-point between two areas of supply. I have had a large experience in estimating the cost of these d.c. feeders, and many times I have been appalled at the great cost of running lengths of cable to distant points of a d.c. system. There is no question that the putting down of another substation midway between the two existing substations is far preferable to laying long, heavy d.c. feeders, from the point of view of cost. The only point which to my mind requires discussion is the justification or otherwise of an automatic substation as compared with a manually operated substation. On page 422 the author gives the running charge of the manually operated station as £1 305, as compared with £255 for the automatic substation. The author provides for a double-shift substation, and for three shifts, which means that he must have at least six men to carry out the work, and I take it that a large proportion of the cost quoted will represent wages. It can be done for less than that. In Glasgow, the smaller substations have been for many years worked by a single operator per shift, and I have, so far, never had any reason to regret it. The obvious danger in carrying out such a policy is, of course, the possibility that something might happen to the single man in the station, but so far we have been fortunate, and we still run in that way in the small substations. Further, by making the station semi-automatic we can dispense with the night-shift man altogether. It costs but a few pounds to add a very simple equipment which will shut down the rotary converter at any predetermined time. The afternoon shift man sets it to shut down at a certain time and leaves the machine running, and the man who comes in to take over the morning shift finds it shut down. That system can be adopted in quite a number of stations in Glasgow ; we have done it with advantage. Halving the figure of £1 305 gives us roughly £650, and dispensing with this third man reduces the figure to £400 or thereabouts. This figure compares much more closely with the author's figure of £255 than the figure of £1 305 did, so that whether an automatic equipment should be adopted depends, I think, on the cost of maintaining it. I rather think that it will come out at quite a high figure, perhaps more than the £93 quoted by the author. The man who looks after it must be highly skilled and will require quite a good wage, and it is a question of how much time this very complicated equipment will take to maintain, as to whether automatic working is justified or not. I should be glad if the author would divide the cost of the automatic equipment, stating separately the cost of the equipment excluding wiring and erection, and then the cost of the erection and wiring. Has the author any charts showing the number of times the rotary converter is started up and shut down in the course of, say, a week's running? Is the additional space required for the automatic equipment a serious item? The switchboard appears to take up a fairly large space but not to an extent which would present any difficulty or cause greater expense in the equipment when completed.

**Mr. A. P. Robertson:** The author has given us a very clear insight into the working of an automatic substation and the various relays required. On the system which he has described, there were, I think, 42 relays, but there is another equally good system which has only 30. A reduction of 12 relays is a great advance. In regard to the rotary converter, the tap-starting machine with brush-lifting device will not, I think, perhaps last quite so long without trouble as a self-synchronizing rotary converter. The brush-lifting device has, so far as I know, not been altogether free from trouble, and I think that to revert to the tap-started rotary converter is a retrograde step. Of course, I understand that in America they have recently gone back to tap starting. Mr. Mitchell has dealt with the question of costs. The author states that the cost of the automatic gear, over and above the cost of the manually operated gear, is £1 800. The cost of our semi-automatic substations in Glasgow was £110 each. There are four of them equipped with this semi-automatic gear, and they are run with one man per shift and two shifts per day. The wages of the two men thus required amount to £312 per annum. These men, in addition to running the substation do all the cleaning work and keep the machines in order—an additional saving. They also do the clerical work, i.e. writing up log sheets and statistics. One of the disadvantages of a totally automatic substation is that there are no records unless recorders are used, and the fewer recorders the better, as they require much attention. It is very difficult to get a recorder that will ink for more than a day without attention, and trouble is caused by the paper sticking. The author mentions that he has circuit breakers on the feeders. One of the difficulties with circuit breakers is that, if they are not operated occasionally, when they are required to operate they stick, and recently we in Glasgow had to consider whether to install circuit breakers or fuses on our feeders. On all feeders protection is by means of fuses, it having been decided that, owing to the difficulty of keeping the circuit breakers in condition, fuses were better. A breaker would require to be operated at least once a week to keep it in order, and that would have to be done manually, otherwise it would be necessary to have another breaker alongside to close while testing, in order to prevent shutting down the district. We thought of overcoming the difficulty by putting a switch across the breaker and closing the switch when the breaker was opened for testing. On page 422 voltage regulation is referred to. I should be glad if the author would indicate the type of regulator used, although I gather from the lantern slide which he showed that another regulator is under consideration. In the semi-automatic substations in Glasgow we have no regulator; we do not find it necessary with rotary converters, as they regulate themselves to a great extent. The man going off shift leaves the automatic gear ready and the voltage a little low, and when the load goes off there is absolutely no kick. My house is supplied from one of these substations, and when it used to be manually operated I could always tell when the man went off shift. It is now midnight in summer and 2.30 a.m. in winter before the substation is shut down, and no kick is experienced. In regard to voltage regulation, in an automatic substation the voltage has to fall a predetermined amount before the station comes in, and it is surprising how much that does occur, especially where there is a cooking load. The voltage would drop and the automatic substation would come in and raise the voltage quickly; then if the load fell, the substation would go out again, when the voltage would again fall. I think that consumers would object to that; we were on the verge of having complaints before we introduced the semi-automatic substations. How often does the automatic equipment start up and shut down? It would be interesting if the author could give a voltage chart and load chart for a day. Although we have two men generally, we run one of our substations all the summer with one man, the other man being available for going round the other substations for holiday reliefs.

**Mr. O. Ellefsen:** A previous speaker has referred to the complicated nature of the scheme, and it is undoubtedly essential to have it as simple as possible in order to run without interruption. When automatic gear first came into use for industrial purposes engineers wanted it to be so extensively interlocked that an automatic controller had more interlocks than main contacts. They found later, however, that it was a better policy to reduce the interlocking considerably, and they got more reliable and cheaper gear. It has been mentioned that there are other schemes for the automatic operation of substations. In some of them, instead of depending entirely on relays, a master controller is used, usually motor driven. In that way a great number of relays and interlocks are dispensed with. There is not at the present time the same likelihood of relays going wrong as there used to be, because of the experience gained with relays for automatic gear for industrial purposes. There are also other branches of electrical engineering where a great many more relays are used, e.g. in automatic telephone exchanges, and there is surely no question of them not operating satisfactorily. Was the use of pilot wires considered for starting up the rotary converter, instead of depending on the voltage-drop? Pilot wires from the central station would enable the engineer at that point to start up the rotary converters in the different districts as the load conditions changed. Mr. Mitchell and Mr. Robertson have referred to the automatic equipment controlled by a time switch. The great variation in the daylight from one day to another, especially in a city like Glasgow, and particularly during the winter months, must be very marked. On one day the light may be quite good in the early morning and bad in the forenoon, and the next day may be perfectly clear throughout. The sudden descent of a fog might cause trouble when a substation is controlled by a time switch only. I understand from the paper that the voltage regulator used was operated by a battery. What is the reason for that, and why is it operated across the ammeter shunt instead of across the d.c. voltage? Has it ever been found that the polarity of the converter has not been correct after the first attempt to correct it by the automatic control? With regard to relay (12) which cuts in the limiting resistance, it appears from the diagram that when the limiting resistances are cut out the current will immediately be reduced, and the tendency would be for the relay to operate again and cut it out. How is that prevented? When the equipment stops under normal conditions, the position of the voltage regulator will evidently be in the position for the lowest voltage. Is that the best position of the regulator for starting? There is one point which has not been mentioned and which appears to be greatly in favour of automatic substations as regards cost. Hand-operated substations are undoubtedly likely to run longer than automatic substations on uneconomical loads. As soon as an automatic substation reaches an uneconomical load it will cut out. A hand-operated substation will run on until it is noticed by the operator, and even then the operator will frequently prefer to let the machine run on rather than shut down and start it up again.

**Mr. E. Seddon:** My remarks can only be of a general character, as I have had no practical experience of automatic substations. The paper is a warning to supply engineers to give attention to the design of automatic substations. The electricity supply substation is passing through much the same stages as the telephone exchanges did, and these are gradually becoming automatically controlled. Like some of the previous speakers, I should like to know why the tap-started rotary converter was chosen. Was it because the machine was cheap, or was it because this type of converter lends itself better to automatic control? There are other machines on the market which will give constant polarity and which will not, I think, require such a large number of relays as the one under discussion. There is no doubt that the trend of present-day practice is to make machines automatic in operation. Electricity is so flexible, and instruments are so well designed, that substation plant and similar machinery will become more and more automatic as time goes on. Progress in this line is built up on a system of copy and improvement, and I take it that the author will have no objection to showing this new substation to members if they happen to be in the Liverpool district. I do not see why the author should debit the manually operated substation with the cost of two men. In Edinburgh we have only one man per shift, but I realize why two men per shift are recommended by the author, and I think it will become necessary in order to ensure the safety of the attendants for them to ring up the power station at definite intervals of time. If the attendant fails to do so, immediate steps would be taken to find out the cause.

**Mr. G. Henderson:** I should be glad if the author would say why, for a combined lighting and power load, he considers that the automatic substation started and stopped by voltage-drop and load conditions is a better proposition than a substation controlled by a pair of pilot wires. On a purely automatic system we can conceive a number of converters running with a load just above the setting of the low-load shutting-down relay for a fairly long period, as on the type of load mentioned by the author on page 417 there may be clearly defined periods of peak loads with wide valleys. This means that the converters may be operating at low loads with corresponding low efficiencies. If such substations, in addition to having all the features of a purely automatic substation, were also controlled from a centre by a pair of pilot cables which could be arranged quite easily to give all the advantages of a manually operated substation, the overall efficiency would be greatly improved by having the control of the load on the substations. Also, all the substations would be under the control of one engineer, which would be an advantage in the event of a serious shut-down on the system, as all the control gear on the d.c. side could be paralleled at the same time. This method certainly calls for pilot cables and a few more relays, but it has many advantages and in many cases pilot cables exist. On a traction system, voltage and load conditions should certainly start and stop the converters, as load fluctuations are more frequent and a greater voltage-drop can be allowed before switching in the converters. The scheme as outlined by the author is certainly very ingenious and, unfortunately, all the relays and devices mentioned are necessary. One feels that any other method or type of machine which could reduce the number of devices would be very welcome, no matter how satisfactory the scheme described may be. In regard to the conditions set out on pages 417 and 418, I should like the author to explain more fully how certain devices operate in practice. How sensitive is the low-voltage starting relay? That is, supposing that the voltage drops to the predetermined value, and that during the time-lag on the relay the pressure rises again, what is the rise in pressure before the relay stops? Again, does the author find that the type of thermostats described give entire satisfaction without frequent calibration? Lastly, why does he not use compounded converters instead of automatic regulators?

**Mr. D. Martin:** Schemes for fully automatic substations have been discussed for years past and possibly still would be but for the fact, admitted by the author, of the prohibitive costs of alternative methods of meeting the increased demands for supply. While the Liverpool electricity supply undertaking is to be congratulated on the steps they took in the manner described in the paper, still in a sense they were compelled, by force of circumstances, to move in that direction, and from that point of view the pride of place to which Liverpool would be naturally entitled is by that amount discounted. I am more concerned with the manufacturing side and would emphasize the fact that manufacturers have had ready for years past, schemes based on practical experiments. The delay in installing such a scheme cannot be laid at the door of the manufacturer but rather at the door of the timorous station engineers, of whom there are still a number. In this connection there are some with more than a healthy respect for the Government official and the restrictions and regulations of Government departments. Is this as it should be? As a rule bureaucracy is restrictive and not constructive, and we in this country, if we would advance, must see to it that nothing is allowed to stifle the progress of applied electricity, which the late war proved to be practically the life blood of the nation in its industrial uses. The present Electricity Commissioners are models in this respect, but they unfortunately are not the only Government officials involved. The scheme outlined by the author follows typical American practice. In an initial scheme of this nature (and particularly as it is for a municipal undertaking) I am sure that many members would like to know whether consideration was given to any of the British schemes. There is one at least in which the number of relays is something like 30 per cent less than that used at Liverpool. Some previous speakers have referred to the question of the reliability of relays. If they are not reliable then it is an advantage to reduce their number, but on the question of reliability surely it is rather late in the day to question them, with all the experience now available. On this point I have not the slightest hesitation in assuring station engineers that we can now almost imitate the human touch with these instruments. The automatic telephone exchange is a case in point. All that is necessary is to give the manufacturer the requirements and he will do the rest. The author very briefly refers to remote control already in existence. Can he give any results of the Hull system with pilot wires, which has been running, I understand, for the past 25 years? Glasgow too, 20 or more years ago, in its early stages had battery substations for the maintenance of voltage at the extreme ends of long feeders. Can the author say how this was done? I am aware that, owing to the enormous increase in load and for economic reasons, these battery substations were scrapped, but at the time they performed their functions in the same way as the Liverpool station is now doing for the first time by other means. In Glasgow, too, there are a number of semi-automatic substations which meet possibly 80 per cent of the Liverpool requirements. I mention these points merely to emphasize the fact that Liverpool is not entitled to all the honours claimed for it in the paper. Had the necessity for fully automatic substations arisen in Glasgow I feel sure that with their usual progressiveness (they had the first super-power station) they would have installed one. Liverpool and Glasgow are very similar in many respects, but Glasgow is more homogeneous with its heavy load centres and where it is more practicable to have 20 000-volt substations properly manned. Unlike Liverpool, however, it is not so liable to heavy fluctuations on isolated feeders. Even on this point the author admits he finds it safer to man the automatic substation on race days and the like, which rather discounts the advantage of his automatic substation.

**Mr. P. J. Robinson** *(in reply)*: Several points raised by Mr. Mitchell have been dealt with already in my replies to other speakers. The extra space required for relay panels is very small, and they need not necessarily form part of the main board.

The figures given by Mr. Robertson are very interesting; the costs have been dealt with elsewhere. As the feeders are looped into the station in the case under review, there is no difficulty in operating the feeder contactors as often as is found necessary. No difficulty has been experienced with voltage regulation, as the station does not come in immediately on a fall of voltage.

In reply to Mr. Ellefsen, the question of pilot wires has been dealt with elsewhere. The polarity of the converter, if incorrect, has always come up correctly after one operation of the field change-over switch. Voltage regulation is effected by means of a contactor which is operated by a shunt. As the load increases, a contactor cuts out the field resistances sufficiently to increase the voltage by a given amount.

Mr. Seddon's remarks have been considered elsewhere in my reply.

In reply to Mr. Henderson, the low-voltage relay is extremely sensitive and is in fact a voltmeter movement. The thermostats have given no trouble, and there does not appear to be any reason why they should require frequent attention. There is a great deal to be said in favour of compounded converters, but in this case it was thought advisable not to depart from our standard practice of using shunt converters on both lighting and traction loads.

All the points raised by Mr. Martin have already been dealt with.

# A PHYSICAL PHENOMENON AND ITS APPLICATIONS TO TELEGRAPHY, TELEPHONY, ETC.

By Alfred Johnsen and Knud Rahbek.

(*Lecture* delivered before* The Institution, 26*th May*, 1921, *supplemented by an account of later investigations : MS. received* 29*th May*, 1923.)

In the course of some experiments in telephony, the authors discovered in 1917 that in some cases an appreciable adhesion occurs between two bodies in contact with each other, when a difference of electrical potential exists between them.

Leading up to this discovery and its later development by the authors was the observation that a weak sound was produced when a finger was rubbed lightly on a metal surface while an alternating current of audio frequency was passing between the finger and the metal.

Later investigations by the authors and others have shown that the latter phenomenon has been observed by numerous persons, especially in recent times, when, in consequence of the wide application of alternating current, the phenomenon has been observed on numerous occasions. These observations, however, have generally been disregarded, and no systematic investigation of the true nature of the phenomenon seems to have been carried out. The only suggestion of practical use seems to be due to the well-known American inventor, Dr. Elisha Gray, who in 1875 patented the use of a rotating metal drum which would reproduce sound when touched by the operator's finger.

Immediately after their observation of this phenomenon the authors commenced a series of experiments with different materials, and soon attained such powerful and distinct effects that a systematic investigation of the true nature and the necessary conditions for the production of the phenomenon was decided upon. During this investigation, which was successfully completed in 1918, several possibilities of the practical application of the effect suggested themselves to the authors, who devoted the following two years to the technical design of various apparatus based on this effect, chiefly for use in telegraphy and telephony, as well as to the solution of certain technical problems which soon presented themselves in this connection. Ultimately, in 1920, apparatus was produced which was extremely reliable and constant in action, and this was for the first time described and exhibited in Copenhagen in 1920, at the electrotechnical congress held on the occasion of the centenary of the discovery of electromagnetism by Oersted. The most remarkable feature of this apparatus, chiefly telegraph-recorders and loud-speaking telephones, is constituted by the fact that, although powerful mechanical effects are produced by such apparatus, the current consumption is practically nil.

The production of sound when one's finger rubs a metal plate can be shown to be due to a variable adhesion between the finger and the metal. The natural adhesion is increased when the current is passing, and the direction of the current is in this case of no importance. With a pure alternating current a note is therefore heard which is one octave higher than that produced in an ordinary (polarized) telephone by the same alternating current. This "electrical adhesion" can, by means of other materials than the finger and by the application of direct current, be demonstrated in a continuous and highly intensified form, as shown in the following experiment. This illustrates the very considerable adhesion set up between a metal plate and a slab of lithographic stone, if the two parts are connected to a 440-volt d.c. supply. Plane, polished lithographic stone brought into contact with plane, polished metal shows the electrical adhesion in a much higher degree than does the human skin in contact with metal.

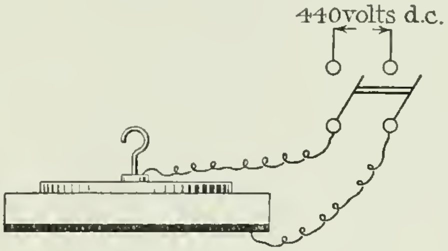


Fig. 1

*Experiment.*—A slab of lithographic stone about 2 inches thick (see Fig. 1) is placed on a table. The underside of the stone is covered with metal foil (as a cement for fastening the foil, fish-glue or, better, water-glass may be used). It is essential that the cement should not possess highly insulating properties, as, for instance, shellac and most varnishes do. The upper surface of the stone is plane and very smooth, preferably polished, and on this is placed a plane, polished disc of metal (brass) 2 inches in diameter. If the metal foil on the underside and the metal disc are connected to a source of E.M.F. (440 volts d.c.), the disc will cling tightly to the stone. By means of a scale balance it can be shown that more than one kilogram is necessary to separate the disc from the stone. An equally large force is necessary to move the disc along the surface of the stone, thus showing that a considerable friction has been set up between them. The electrical resistance of the stone is very high, and therefore the current passing between the stone and the disc is very small, in spite of the high voltage applied. As the stone possesses some hygroscopic properties, its conductivity is dependent on the humidity of the surrounding air, so that an exact value of the current cannot be given ; moreover different specimens show different conductivities. Generally, however, the current will not exceed a few microamperes. That this is so can be shown by the fact that there is no perceptible diminution of the adhesion when the current is passed through the body of the operator. If the circuit is broken, the adhesion disappears.

---

* The commercial exploitation of the subject-matter of the Lecture is protected by British Patents 144 761, 146 747, 194 747, and by Colonial and Foreign Patents.

It is obvious that there are some points of resemblance between this device and an electromagnet. Both have the property of producing mechanical force by means of electricity. The very small current sufficient for the operation shows that the adhesive effect can, in certain cases, be used with advantage instead of electromagnetism. An essential difference, however, lies in the fact that an electromagnet is able to attract its armature from some distance, and thus do mechanical work, whereas the electric adhesion is only manifest between two surfaces which are in contact with each other. It is true that if one of the surfaces is elastic and only partially in contact with the other before the E.M.F. is applied, a certain small amount of mechanical work can be effected, as will be shown later, but generally the utilization of the electrical adhesion is confined to the governing of extraneous forces, and its use will be advantageous where only small currents are available for this purpose, and also where relatively large forces are to be exerted on bodies of small mass. While the attraction exerted by an electromagnet on its armature is, within limits, proportional to the mass of the latter, the electrical adhesion is independent of the thickness of the metal : a thin, light metal foil will adhere to the stone quite as well as a thick, heavy disc.

The principal explanation of the nature of the electric adhesion, as given by the authors in 1917, is as follows :—

The lithographic stone belongs to a class of substances which will here be termed semi-conductors. These substances are solid electrolytic conductors, and they combine a moderate internal resistance with a relatively high contact resistance to conducting solid bodies applied to their surface, if no conducting liquid, cement or the like is interposed between the surfaces. The true nature of the contact resistance proper has not yet been completely revealed, but it appears that the very thin film of absorbed air which ordinarily covers the surface of solid bodies plays a certain role, as does the fact that two solid bodies are in reality in contact in relatively very few points, even if the greatest care is taken to fit them exactly together. It may be mentioned that the contact resistance exists even with thin, bright tinfoil which is smoothed very carefully on the semi-conductor, while it is absent with mercury. Further, it appears that a relatively large potential difference is necessary to draw electrolytic ions, which in this case are the only carriers of the current, across even the smallest air space, while electrons pass freely across even a light metallic contact. That the majority of the ions have to cross a certain free space at the point of contact is also made probable by the fact that the value of the contact resistance is by no means constant, but decreases with increasing potential difference. Indeed, the current is over a wide range nearly, but not quite, proportional to the square of the E.M.F., the corresponding curve in many respects resembling the lower part of the characteristic curve of a thermionic valve.

If now (see Fig. 2) H is a semi-conductor, I and II metal plates in contact with H (for the sake of clearness a small air-gap δ is shown between H and each of the two plates), then if a potential difference $E$ be applied between the plates, the diagram of the distribution of the drop of potential from I to II will be as indicated. Across the semi-conductor there is only a small drop of potential $p$, while at each point of contact, on account of the large contact-resistance, a relatively large drop of potential, namely $\frac{1}{2}P$, takes place ($E = P + p$). This distribution of potential can easily be verified experimentally by means of an electrostatic voltmeter.

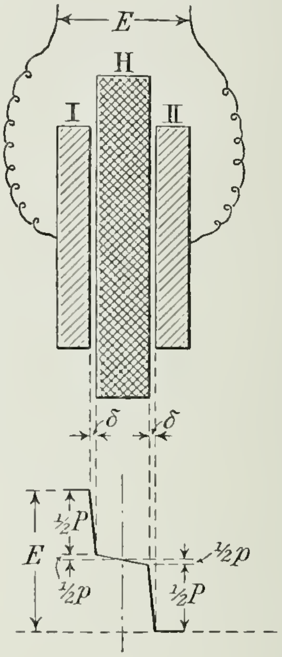


Fig. 2.

It is obvious therefore that there must be a very large electrostatic attraction between the semi-conductor and each of the plates, if it is remembered that the attraction between the two plates of an air condenser is inversely proportional to the square of the distance between the plates, the potential difference being maintained constant. The air-gap being in this case theoretically infinitesimal, an infinitely large attraction should be expected. In practice, however, only a limited attraction is manifested, but, nevertheless, an unusually strong attraction can be obtained with relatively moderate potentials.

The attraction is, as has already been mentioned, also manifested by an increase of the friction between H and each of the plates I and II. If a sufficiently high potential difference be applied, a considerable force is necessary to cause I or II to slide on H. It is especially this increase of friction that has been utilized for the various apparatus which will be described in the lecture.

The attraction varies somewhat with different semi-conductors, but it is mainly dependent on the interior conductivity of the material and the degree of polish which can be imparted to the surface. Amongst those which the authors have found to be most effective are the lithographic stone, some sorts of slate, limestone and marble, flint, agate, species of jasper and other silica minerals (not pure quartz, which is highly insulating), and many organic substances such as bone, ivory, gelatine, cellophane, pyroxyline, some sorts of paper, etc. When dry, the human skin shows semi-conductive qualities, and this explains the production of sound by a finger rubbing a piece of metal. As cold metal is apt to condense moisture from the skin, the effect is increased if the metal is slightly heated. The thin skin of the wrist or forearm gives better results than the horny skin of the finger-tips. That skin possesses a large contact resistance to dry bodies is well known, as is also the fact that the electrical resistance between two fingers or even from hand to hand is reduced to a fraction of its initial value if the skin is moistened.

The authors have in most of their apparatus used agate, chiefly because this stone possesses adequate conducting qualities, and because it is hard and is capable of receiving a high degree of polish. With it, a surface attraction several times larger than that of the lithographic stone can be obtained.

It is difficult to give a satisfactory definition of semi-conducting materials, as every conducting solid might be so termed and will certainly show some degree of surface attraction. The semi-conductors proper are, however, easily differentiated from the insulators proper, as the orders of magnitude of their conductivities are quite different. A piece of slate or agate will under normal conditions possess a conductivity many million times larger than that of a similar piece of glass, hard rubber, mica, sulphur or similar substance.

Several well-known soluble salts possess such interior conductivity, independent of atmospheric moisture, that they may be classed as semi-conductors, but their surface resistance is so widely dependent on the humidity of the atmosphere, and their mechanical properties are so inferior, that no technical application has so far been made of them.

In addition to the above, the chief group of semi-conductors proper may be said to consist of materials which are able to absorb and retain moisture, and these again can be divided into two classes, (1) finely porous substances, and (2) colloidal substances, which permit of the diffusion of moisture. Both classes are to a certain degree hygroscopic.

To the first class belong chiefly inorganic substances, e.g. slate, marble, steatite, agate, flint, etc. Their conductivity is chiefly due to atmospheric moisture absorbed by their innumerable pores, and the conductivity disappears practically entirely if the material is heated well above the boiling point of water. Agate and flint form a transition to the colloidal substances.

To the second class belong chiefly organic substances, e.g. skin, gelatine, cellophane, pyroxyline, collodion, albumen, etc., which swell more or less when immersed in water, and which also lose their conductivity nearly completely if heated sufficiently in the dry state.

On this chief group of semi-conductors a flow of current through the material has much the same effect as heat on the conductivity. If a constant potential is applied the current will steadily diminish, the moisture being, in the vicinity of the electrodes, gradually decomposed by electrolysis. When an appreciable layer next to the electrodes has thus been dried, a considerable diminution of the surface attraction is observed, and ultimately the attraction will practically disappear in the course of some hours or days, according to the circumstances. On the other hand, the conductivity and consequently the full attractive power will be restored if the material is left to itself for a day or two. How this inconstancy has been eliminated in the practical apparatus will be described later.

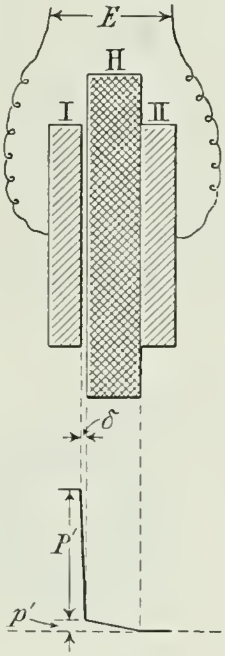


Fig. 3.

If one of the metal plates (II in Fig. 1) is connected to the semi-conductor by means of a sufficiently conducting cement or glue, the contact resistance, and consequently the drop of potential, will almost entirely disappear at this place. As shown in Fig. 3, nearly the full potential will appear between the other plate, I, and the semi-conductor; the interior drop of potential $p'$ is ordinarily only some few per cent, sometimes a fraction per cent, of the total potential $E$. The values of $P$, $p$, $P'$ and $p'$ in Figs. 2 and 3 only correspond if the value of the contact resistance between H and I is assumed to be independent of the drop of potential, but this is, in reality, not the case.

It is obvious that a larger attraction is obtained between I and H in the case illustrated in Fig. 3 than in that shown in Fig. 2; in the actual apparatus the contact resistance between the semi-conductor and one of the electrodes is, for this reason, eliminated as far as possible.

As only a relatively small drop of potential exists in the interior of the semi-conductor, the thickness of the latter has little bearing on the magnitude of the attraction. Indeed, the lithographic stone would give very nearly the same attraction if its thickness, instead of being 2 inches, were only a fraction of an inch. It is, of course, a practical advantage that a fairly thick and therefore robust semi-conductor can be used. This point is particularly emphasized because attempts have previously been made by others to construct electrostatic relays by the insertion of a thin dielectric between two conducting plates. As, however, the attraction across a dielectric is inversely proportional to the square of the thickness of the latter, an extremely thin layer of dielectric (1/2 000 inch or less) has to be used in order to obtain a reasonable sensitivity, and thus the dielectric in such apparatus is very delicate and liable to be punctured. The earliest apparatus of this description appears to be due to the American inventor R. A. Fessenden, who used mica as a dielectric in a telegraph-recorder, which was operated by means of alternating current. It is not possible to operate such apparatus by means of direct current, as a surface charge (similar to the well-known residual charge in mica condensers) will in a short time collect on the dielectric and counteract the attraction across the latter. This again means that telephonic apparatus cannot be developed on this principle, as a continuous polarization potential is necessary in all electrostatic telephones.

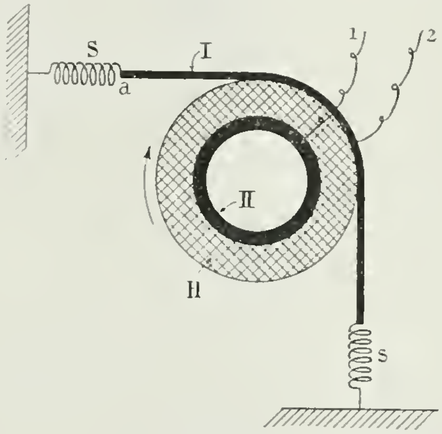


FIG. 4.

The general arrangement of the semi-conductor in relays, etc., is shown diagrammatically in Fig. 4. The cylindrical semi-conductor, H, is mounted on a shaft and is kept in continuous rotation by means of a motor (not shown); the direction of rotation is indicated by the arrow. Round a part of the circumference of the semi-conductor is placed a metal band, I, which at the point, a, is connected to a spring, S. A weaker spring, s, serves to keep the band, I, taut. Inside the semi-conductor is shown the metal lining, II, which is to be cemented to the semi-conductor. In reality, this metal lining is in our more recent apparatus replaced by a liquid which fills the interior of the semi-conductor and conducts the current from the central shaft, as will be described in detail later. In Fig. 4, II therefore only indicates the position of the interior conductor. 1 and 2 represent the leads supplying the potential; lead 2 may, for instance, be connected to the base of the spring, s, and lead 1 to a slip-ring, though it is generally sufficient to connect it to the bearings of the shaft carrying the semi-conductive cylinder.

So long as a potential difference is applied between 1 and 2, the increased friction between the cylinder and the band maintains the spring, S, stretched, while this spring will contract if the potential difference decreases or disappears entirely. The members to be operated by the relay may thus be coupled to the point, a, where the band is connected to the spring, S.

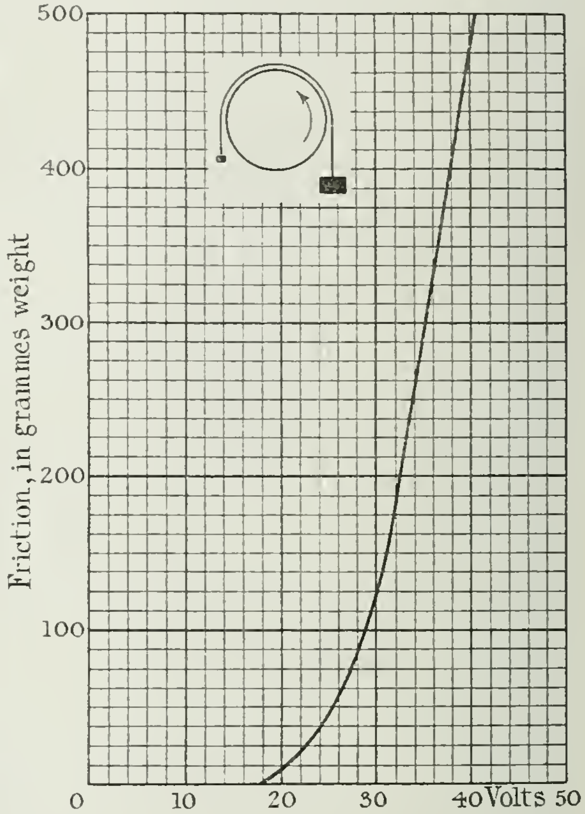


FIG. 5.

This arrangement forms the basis of a number of different apparatus.

If the point, a, is connected to a recording stylus, an ink siphon or the like, the apparatus may be used for receiving telegraph messages, and if relay contacts are operated in the same way the apparatus forms a telegraph transmitting relay which may be used either for receiving or transmitting purposes.

If the spring, S, is replaced by the diaphragm of a sound-box, the apparatus may be used as a loud-speaking telephone.

Instead of a cylindrical semi-conductor encircled by a metal band, a metal cylinder partially encircled by a flexible semi-conductor, for instance thin gelatine, could be arranged, but this is not used in our later apparatus.

It would be thought that the electrostatic attraction at the surface of a semi-conductor would be proportional to the square of the E.M.F. impressed, according to the law for an air condenser. In reality, however, the attraction increases much more rapidly; it is in fact nearly proportional to the fifth power of the E.M.F. This is, however, only approximate and only valid from about 25 to 300 volts. At higher potentials the attraction rises more slowly, and ultimately a strong ionization partly breaks down the contact resistance, so that a decrease of attraction may actually be observed. In Fig. 5 the ordinates represent the friction between a small cylinder of agate and a piece of thick tinfoil placed round half of the periphery. The increase in friction due to the electrostatic attraction is proportional to the latter. It will be observed that, as far as the curve goes, the friction is approximately proportional to the fifth power of the E.M.F.

The fact that the attraction increases more rapidly than the second power of the applied potential has not yet been fully explained. The considerable attraction at higher potentials no doubt helps the attracting surfaces to come into more intimate contact. On the other hand, various observations made by the authors point to the fact that this is not the entire explanation. Possibly, a phenomenon analogous to the space-charge in electron tubes may be a contributory cause. The very rapid rise of the attraction is, moreover, found only if the surfaces are in very intimate contact. If the surfaces are hard and rigid and do not fit very closely together, the attraction will generally not be found to rise more rapidly than with about the third power of the potential, and if the surfaces are quite rough the square law of electrostatic attraction will be found to be nearly fulfilled. This is, of course, only to be expected, as in this case the greater part of the surfaces is separated by a definite, un-ionized air space.

If a semi-conductor capable of absorbing water is soaked with a liquid electrolyte, such as a salt solution, and then allowed to dry, it will generally be found that both its interior resistance and its contact resistance have diminished. If suitable salts are used for this impregnation, the interior resistance is reduced to a smaller amount than the contact resistance, so that the semi-conductive qualities of the material may be enhanced. It is thus possible to impart a desired conductivity to the majority of semi-conductors—a fact of vital importance, because a certain conductivity is needed for most practical applications, as will be explained later in the lecture.

The conductivity of such impregnated semi-conductors is, however, still very inconstant when current is passing through the material, because the absorbed moisture is still being dried off, and, moreover, the salt itself will gradually be decomposed by electrolysis.

Attempts were made by the authors to secure a constant conductivity which might be sufficient for practical purposes, and they found that some moisture-absorbing semi-conductors could, when in the form of a hollow cylinder, in which water or an aqueous solution was present, absorb and remain soaked with the water or the solution without their exterior surface becoming moist. Agate (but not slate, lithographic stone, etc.) shows this quality in a very pronounced degree. This material is unable to absorb any large percentage of water, so that its conductivity is not excessive even if it is fully soaked with moisture; on the other hand, when current is passed through it the small percentage of moisture on the surface disappears rapidly. If a hollow cylinder of agate is filled with suitable electrolyte, moisture will, however, diffuse from the interior to the point where the metallic conductor touches the outer surface, and this is sufficient to prevent the conductivity near the surface from decreasing below a certain value. This diffusion is, however, so slow that the outside of the agate cylinder keeps perfectly dry on account of the evaporation. On the other hand, only the moisture which, by slow diffusion, has actually reached the surface will be evaporated, as practically no circulation of air can take place inside the extremely fine pores. The loss of moisture by evaporation is therefore extremely small, in spite of the stone being in reality entirely and continuously soaked with moisture. In our actual apparatus such hollow agate cylinders are used. These cylinders are mounted between two bosses on a shaft, so that a space for the liquid is formed between the shaft and the interior surface of the cylinder. The shaft and bosses are silvered in order to prevent corrosion. The electrolyte is substantially a solution of a somewhat hygroscopic salt, which will not easily crystallize in the pores of the agate. It has been found that the formation of crystals in the pores of the agate will produce partial cracks and ultimately cause the stone to disintegrate. The loss of electrolyte by evaporation and electrolysis is extremely small, the average life of the filling being at least two years, after which time the cylinder can be refilled in a few minutes. If desired, the electrolyte can be taken up by some absorbent powder such as flour, as is done in dry cells. In order to prevent the electrolytic formation of free hydrogen inside the sealed cylinder, the shaft of which is ordinarily the cathode, an oxidizing substance such as manganese peroxide is added to the electrolyte.

In the foregoing remarks, the authors have not dealt with the influence of the polarity of the semi-conductor on the contacting conductor. If both the internal resistance and the surface resistance of the semi-conductor are independent of the polarity of current and potential, it is to be expected that the attraction will be substantially independent of the polarity, and this is verified by experiment. These conditions can be approximately realized by means of a dry lithographic stone, as has been shown, especially if the stone is heated a little above the air temperature. Upon reversal of the polarity, the current and the attraction will be found to have remained approximately constant. If, however, the semi-conductor contains a considerable amount of moisture, or if it has been impregnated with an electrolytic salt solution and especially if it is hollow and filled with an electrolytic fluid, as the agate cylinder above described, the effect of reversal of polarity is very marked. If the semi-conductor is made negative relative to the contacting conductor, the current will, after the application of a constant potential difference, gradually decrease, but only to a certain extent in the case of the filled agate cylinder, as already mentioned. On the other hand, the attraction will remain substantially constant from the first moment, a small increase being, however, observed in the course of the first few minutes if certain electrolytes are used. In the actual apparatus the semi-conductor is made negative, and is so chosen as to give a sufficiently constant attraction for practical purposes. The constant potential necessary for constant attraction is generally easily attained in spite of the inevitable variation of current, as the total current consumption is so small that it constitutes only a negligible load, even on high-resistance circuits.

If the semi-conductor is made positive relative to the contacting conductor, the current will gradually increase after the application of the potential, and the attraction will generally be found after a few minutes to have decreased considerably. In this case the interior resistance of the semi-conductor remains substantially constant, but the contact resistance gradually diminishes until finally only a very small drop of potential exists at the surface. In some cases the attraction will practically decrease to zero in a few minutes, while the current increases to more than 20 times its original value. If the potential is reversed, the original small current and corresponding large attraction do not reappear immediately, but generally in less than one minute.

The cause of the reduction of contact resistance just described has not yet been exactly stated by the authors. It is certainly due to the flow of current, and it appears that moisture is carried with the current to the surface of the semi-conductor, the effect being probably intimately related to electro-capillarity. It may be mentioned that the effect has been observed both with acid and alkaline impregnation of the semi-conductor.

In connection with this question, a reference to the Edison Electromotograph may be appropriate. This apparatus, which aroused considerable interest in the 'seventies of the last century, has some constructive resemblance to the arrangement described in connection with Fig. 4. Used as a telephone it consists materially of a rotating, porous chalk cylinder, which is entirely soaked with an electrolyte and the surface of which is kept constantly wet, the latter being the exact reverse of the conditions necessary for electrostatic attraction as described by the authors. The end of a flat, elastic metal strip carrying a contact point of platinum-iridium slides with a definite pressure on the chalk cylinder, so that a certain natural friction is set up between the cylinder and the contact point. The metal strip carrying the latter is connected to a diaphragm. If now a direct current flows between the cylinder and the metal point, the cylinder being connected to the positive pole of the source of supply, the natural friction is diminished as long as the current is in existence. It is therefore obvious that sound may be reproduced from the diaphragm if an alternating telephone current is superimposed on the direct current. In this case the action of the apparatus can be said to be the exact reverse of that of the electrostatic apparatus here described, as the two classes of apparatus operate with decrease and increase respectively of the natural friction.

The fact that the same polarity which diminishes the natural friction in the Electromotograph will also diminish the contact resistance in the electro-adhesion apparatus * (as the apparatus will here be termed), has induced the authors to make a short investigation of the nature of the Electromotograph effect. As the latter has no direct relation to the subject dealt with in this lecture, the results only will be briefly stated.

The diminution of the friction in the electro-adhesion apparatus is due to a diminution of the attraction and not to a diminution of the coefficient of friction, while the latter is the case with the Electromotograph, where the passage of current produces a lubrication effect and where no electro-adhesion is in existence.

A diminution of the natural friction by means of an electric current can be effected in two ways, namely by the formation of moisture or of gas at the point of contact.

If a current is passed through a porous or colloidal body which is soaked with water or an electrolyte, and the surface of which is moist, but not actually wet, liquid will generally appear under one or other of the electrodes, thus to some extent lubricating the area of contact. The conveyance of fluids in porous or colloidal substances by means of an electric current has been widely described in literature dealing with electro-capillarity, electro-osmosis, etc. The effusion of the liquid is, however, slow at ordinary current densities, and the experiments carried out by the authors seem to indicate that no efficient quick-working relay is likely to be evolved on this principle alone; it should at least be combined with the true Electromotograph effect described below.

In the Electromotograph, in which the surface of the chalk cylinder is kept constantly wet, the lubricating effect is, on the other hand, generally ascribed to the electrolytic generation of hydrogen at the point of contact. This theory is the oldest, but in the course of time some doubt has been felt as to whether it could satisfactorily explain the rapid variations of friction occurring with sound-reproduction, in spite of the inevitable lag which occurs in the generation of the gas. The investigations of the authors have, however, only confirmed the original theory. The process actually taking place at the point of contact can briefly be stated as follows. On the passage of current, hydrogen is generated in the shape of minute bubbles in each of the microscopic pores of the chalk where the metal touches it. The gas is able to exert an enormous pressure, as its volume is many times larger than that of the corresponding amount of electrolyte. The gas and the liquid together form an extremely fine, expanding foam, which counteracts the pressure of the metal spring and thus diminishes the mechanical pressure of the metal on the chalk. Moreover, the foam, which in consequence of its extreme fineness is relatively durable,

---

* The term "electro-adhesion" for the effect has been proposed by various individuals and appears to be very suitable. In Germany the term "*Elektrokollese*," derived from "Elektrische Klebkraft," has been widely adopted.

has far better lubricating qualities than the pure liquid, as the foam is not so easily squeezed out from between the sliding surfaces. In fact, at a certain current density the metal will float on the foam without making any contact with the chalk, and even then the friction will diminish with increasing current, as the thickness of the foam layer will increase. The reason that no appreciable lag is experienced in the action of the apparatus is in part due to the very small amount of hydrogen which is necessary to convert the very thin layer of liquid between the sliding surfaces into foam, and also to the fact that the relatively quick motion between the cylinder and the small contact point substantially prevents any integration effect, so that the amount of lubrication will at every instant be nearly proportional to the rate of generation of the foam, i.e. proportional to the current. If the speed of rotation is very low, or if the contact point is replaced by a band encircling an appreciable part of the cylinder periphery, considerable distortion must be experienced, as in this case a momentary strong current will have much the same lubricating effect as a prolonged weak current, of course within obvious limits.

Returning to the electro-adhesion effect, and before describing in more detail the motor-driven relays with revolving semi-conductor, the authors propose to describe a class of instruments in which the surface attraction itself produces mechanical motion. Under special conditions they found, in fact, that the surface attraction can cause a motion and thus allow a certain small amount of mechanical work to be done.

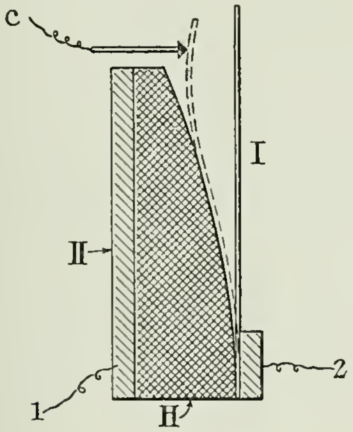


Fig. 6.

Fig. 6 shows a semi-conductor, H, with the metal coating, II. The semi-conductor has a cylindrically curved, smooth surface, in opposition to which a thin, elastic, smooth metal strip, I, is situated. If a certain potential difference is applied between I and II, a considerable attraction will be set up at the different points of the line along which the strip is touching the curved surface tangentially, and also at the points immediately above this line, where the air-gap is infinitesimal. This attraction will cause the strip to assume the curvature of the semi-conductor along this line, and in this way additional new points of the strip will come into immediate proximity to the semi-conductor and will also be subjected to a large attractive force. The result is that the entire length of the strip will fold itself round the curved surface, as indicated by the dotted line, and its free end will thus be moved an appreciable distance.

If a contact C is mounted as shown, it will be obvious that the arrangement forms an electrostatic relay, which the authors have developed for various purposes. On the other hand, the movement itself can be utilized for the detection of a potential difference between I and II, i.e. the arrangement can be used as an electroscope. As the attractive force is very strong in comparison with that obtained in a gold-leaf electroscope, the metal strip can be made sufficiently rigid to permit the apparatus to be used in all positions. The authors have accordingly constructed a pocket electroscope suitable for the indication of potentials from about 70 to 700 volts (d.c. or a.c.).

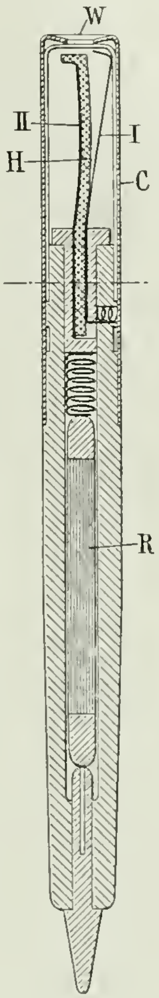


Fig. 7.

In Fig. 7 this instrument is shown in section. It consists of a hard rubber holder carrying on its top the semi-conductor, H, and the strip, I, the thickness of which is about 1/3 000 in. The metal coating, II, of the semi-conductor is connected with the metal point at the base of the instrument through a safety resistance, R, of a few megohms, arranged in the interior of the holder. The strip is connected with a metal cap, C, which protects the upper parts of the instrument and which has a small observation window, W, at the top. The end of the strip is bent at right angles and will only be visible behind the glass when the strip is attracted to the semi-conductor.

The instrument, which in size and appearance greatly resembles a fountain pen, is especially useful for testing whether an electrical wire or any part of an electrical installation is alive. When in use the instrument is held in the hand and its metal point is brought into contact with the object to be tested, the body of the user generally forming a sufficient earth connection, as the total resistance of the instrument exceeds 100 megohms.

As a high resistance is desirable in this instrument, and its use is only occasional, no impregnation of the semi-conductor is necessary.

Referring again to Fig. 4, three main types of apparatus with rotating semi-conductor have been constructed for practical purposes by the authors. These types are : (1) A time-limit relay, (2) a telegraph recorder and relay, and (3) a loud-speaking telephone. Modifications of such apparatus may, of course, be used for special purposes, and the principle of electro-adhesion may obviously be utilized for many purposes for which electromagnetism is suitable.

As previously mentioned, the electrostatic attraction will be sufficiently constant in the general arrangement illustrated in Fig. 4, if H is an agate cylinder filled with a suitable electrolyte. Experience shows that special precautions are also necessary to keep the coefficient of friction constant while the apparatus is in operation. This is due to several circumstances.

If both I and H are brightly polished, and the apparatus is started without the application of a potential difference, the natural friction between cylinder and band will gradually increase, due to the deposit of dust on the surfaces. The hard particles of the dust will act as an abrasive and will thus wear more dust from the cylinder and band. Even if the frictional system is protected from atmospheric dust, a certain natural wear takes place which is at the commencement very small, but which increases rapidly when the least dust has been formed. Any dust or powder originating from the atmosphere or from wear will in the course of time be ground to a very fine consistency and will then adhere quite firmly to the agate, in the same way as fine chalk which is rubbed well into a glass surface, causing at the same time a considerable increase in the coefficient of friction. In this state the frictional system will produce a grinding or squeaking sound and regular working will be impossible. The process is analogous to what takes place when a shaft runs in a bearing which is not lubricated. Lubrication used in connection with the electro-adhesion apparatus does not provide a remedy, as any lubricant, even if insulating, will almost entirely spoil the electro-adhesion effect, as it prevents the intimate contact between the surfaces, and, moreover, the friction will, according to the laws for friction in liquids, be nearly independent of the electric attraction. The only expedient in this case is to arrange a brush which during the working of the apparatus continually and promptly removes any dust that may be deposited on the cylinder, the result being that both cylinder and band remain clean and smooth and the wear on both is reduced to a minimum.

If now a potential difference is applied between the rotating cylinder and the band, new sources of contamination become evident.

As the metal band must be positive relative to the agate, as described, most bands will be attacked by electrolysis, which alone or in combination with atmospheric moisture will produce oxides or salts, such salts becoming smeared over the cylinder and difficult to remove by means of a brush. In recent apparatus the formation of oxides is avoided altogether by the use of a metal which is not attacked by electrolysis in connection with the electrolyte contained in the agate. Another effect remains, however, which, if special precautions are not taken, will in the course of a short time (about one hour under normal working conditions) increase the coefficient of friction to such an extent that satisfactory operation is impossible.

This effect is due to the passage of current between the contact surfaces, the passage having in reality, as far as could be stated by the authors, the character of a discharge,* which causes a slow disintegration of the contact surfaces. This can be made specially apparent if in the experiment with the lithographic stone (Fig. 1) the metal disc is replaced by a disc of hard, polished carbon (a piece of carbon brush or a microphone carbon diaphragm will do). If a pressure of about 200 volts is applied for a period of about 15 minutes, and the disc is then taken away, black carbon powder can be observed on the white stone at all places where real contact has taken place. The lithographic stone is also disintegrated, but to a much smaller extent.

Metals are only very slightly disintegrated, so that in the case of the agate cylinder with the metal band the agate only is perceptibly altered. In this case no loose dust is observed, but the surface of the agate loses its brightness to a certain extent and becomes covered with an extremely thin, transparent layer, which gives rise to an enormous increase of the coefficient of friction. Indeed, if a piece of smooth paper is moved on the surface by means of the finger, the frictional resistance will be felt positively as a sticking. This thin layer cannot be removed by means of a brush or cloth, and will even resist a metal brush. On the other hand, a small amount of an abrasive powder (for instance, flour emery) applied with a cloth will remove it instantaneously, when the polished, smooth surface will be restored at once. Careful investigation by the authors have made it highly probable that this layer consists of colloidal silica, the agate being nearly pure silica. Like many other substances the silica will, when in a colloidal state, adhere firmly to a polished surface, especially to a glass-like surface such as that of the agate, and will in this state produce an enormous frictional resistance; this appears to happen particularly if the substance in its non-colloidal state is very hard, and the phenomenon is also experienced with numerous other materials. The enormous adhesion of certain colloidal substances to glass-like surfaces, and their large frictional resistance, can easily be demonstrated in the following manner. If fine, precipitated, dry fuller's earth (a white powder consisting of colloidal clay) is rubbed well into a clean glass (mirror) surface by means of a piece of rough paper, a white patch will appear which can only with extreme difficulty be entirely removed by means of a brush, cloth or the like. If a piece of smooth paper is moved over the glass surface by a finger, a large resistance to motion will be felt when the patch comes under the finger. The last, nearly invisible, traces of the patch are most difficult to remove, but are easily detected by the friction test. On the other hand, the patch and every trace of abnormal friction is instantaneously removed by rubbing with a hard abrasive powder (knife-powder, tripoli, etc.) by means of a cloth.

---

* At higher potentials (about 350–700 volts), a dim light can be observed at the contact surfaces in a well-darkened room.

As a result of these investigations, the authors in their earlier apparatus made use of a sort of rubber-eraser, containing an abrasive which, in connection with a brushing device, kept the agate constantly smooth and polished, and very good results were obtained in this way. Another method of applying the abrasive has recently been carried out with success, the abrasive being moulded to a cylinder of soft stone, from which minute quantities are continuously supplied to the agate by means of a rotating rubber helix. Experiments, which are not yet concluded, seem to indicate that the use of abrasive can be avoided altogether by employing friction bands of certain very hard metals, thereby introducing a material simplification.

The bands used in the apparatus, which will now be described more in detail, are little more than 1/1 000 inch (0·025 mm) thick and $\frac{1}{4}$ to $1\frac{1}{4}$ inch broad; they cover from one-quarter to one-half of the circumference of the cylinder. The diameter of the agate cylinder is about 1 inch. The frictional resistance set up by a potential of 220 volts is about 1 to 15 lb. in this apparatus, according to the size of the band. Ordinarily, however, an E.M.F. of less than 100 volts is used for the operation.

### The Time-limit Relay.

If, again referring to Fig. 4, the point, a, is connected with relay contacts in such a way that contact is not made until the point, a, has moved a definite distance from its original position, a time lag is very simply introduced into the action of the relay, if the cylinder, H, revolves at a suitable (moderate) speed. If a sufficiently high d.c. potential is applied between 1 and 2, the band will cling tightly to the cylinder, and the relative sliding will cease instantaneously, after which the point, a, will move steadily at the low peripheral speed of the cylinder until contact is made. The time lag can obviously be altered by adjusting either the free path of the point, a, or the speed of rotation. In the actual apparatus the cylinder is preferably driven by clockwork or by a very small low-tension motor with a worm gear as used in electric meters, and the speed chosen for certain purposes is about one revolution in 1 or 2 minutes. If the current is interrupted, the point, a, moves quickly back to its initial position. The potential necessary for actuating the relay is normally about 50 volts, although higher sensitivity can be obtained. The mechanical force available is ample for the operation of any ordinary contacts. If very heavy currents are to be dealt with, the contact device operated by the point, a, is replaced by a trigger device which is released by the point, a, and which in turn releases a heavy contact device or switch. The relay is more specially intended for the operation of bell alarms in radio-telegraphy and telephony, as well as in carrier-current telephony, and also in some special cases of remote control. If in any of these cases the incoming high-frequency energy is sufficient to actuate a sensitive high-frequency indicator (e.g. a sensitive hot-wire instrument), the latter can be fitted with a delicate contact arrangement and the time-limit relay be used as a secondary relay, which again can actuate a bell alarm or any special electric arrangement. The very small current actuating the time-limit relay (about $10^{-6}$ ampere) will not cause even very delicate contacts to stick, the relatively high potential (about 50 volts) ensuring reliable electrical contact even with very light contact pressure. In such cases the use of valves for alarms or any remote control may be dispensed with. If, in other cases, the relay is to be actuated directly by a valve current, the diagram of connections is the same as will be described under the heading " Telegraph Recorder and Relay."

It will be seen that a continuous signal of at least the length of the time lag is necessary to operate the relay, as any premature interruption of the signal will cause the relay to return quickly to its initial position without closing the contacts.

A time-limit relay has also been constructed on the principle of two plane circular discs sliding on each other, one being stationary and connected with the relay contacts, and the other being rotated by clockwork. One disc may be semi-conductive and the other of metal, or both discs may, if desired, be of semi-conductive material. The case of electro-adhesion between two semi-conductors has not been dealt with previously in the lecture; it presents no material difference from the case of electro-adhesion between a semi-conductor and a metallic body.

The continual cleaning of the discs, however, presents such practical difficulties that the cylinder-and-band principle is preferable.

### The Telegraph Recorder and Relay.

A fairly wide field for the use of electro-adhesion is found in telegraphy. Apparatus for receiving (recording), relaying or transmitting purposes can be constructed, and the electro-adhesion principle can be combined with known systems of printing telegraphs, transmission of photographs, etc. Such apparatus can, however, be regarded as modifications or applications of the general arrangement of the telegraph recorder and relay shown diagrammatically in Fig. 8.

Here H, I and II [Fig. 8 (*a*)] represent the friction system. The band I is fastened to a bell-crank lever, V, pivoted at the point, $\sigma$. The light spring, f, holds the band taut. The horizontal arm of the lever is normally pressed against a fixed stop, $s_1$, by means of the strong, adjustable spring, F. The vertical arm carries the siphon or other recording device. In Fig. 8 (*b*) the recording arrangement with siphon and paper drive is shown in side elevation, together with a sample of the record. The operating potential difference is applied between the leads 1 and 2 [Fig. 8 (*a*)] and causes the frictional pull in the band to overcome the pull of the spring, F, so that the horizontal arm of the lever will ascend until it strikes an adjustable stop, $s_2$, the position of which determines the amplitude of the recorded signs. Upon the cessation of the operating current, the strong spring, F, will quickly draw the lever back to the stop, $s_1$. On the vertical arm of the lever is further shown a contact 3, which can touch in turn the contacts 4 and 5 and thus supply double current impulses from a local battery either to a local receiver working with double current, or to a cable or line operating a distant receiver. In each of these cases the record of the apparatus proper may be used as a control record.

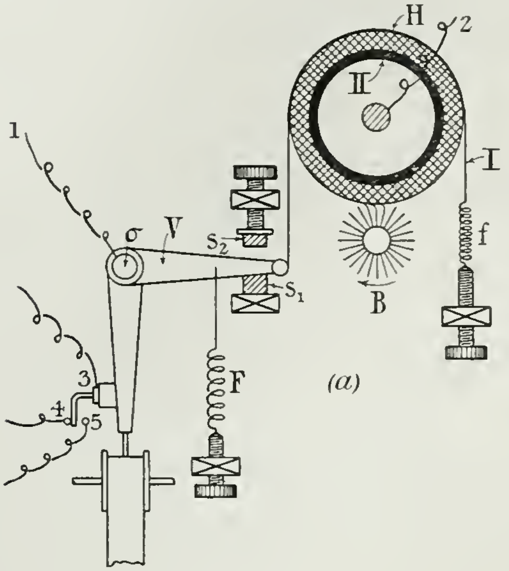


FIG. 8 (*a*)

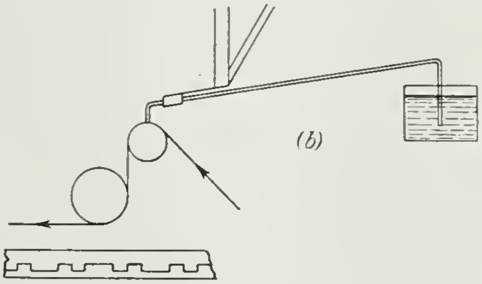


FIG. 8 (*b*).

As the moving parts of the recording system (band, lever and siphon) can be made very light (3 grammes or less), and the operating mechanical force very strong (several pounds if desired), a very large acceleration of the writing mechanism can be obtained, so that a high recording speed is attainable, provided that the peripheral speed of the rotating cylinder is sufficiently high (about 300 r.p.m. of a 1 inch cylinder will suffice for the highest commercial speeds).

For the attainment of high recording speeds, consideration must, however, also be given to the electrical properties of the electro-adhesion system as well as of the circuit in which the apparatus is inserted.

The contacting surfaces of the band and the semiconductor together form a condenser which, in spite of its small linear dimensions, possesses an average capacity of about 2 000 cm in a normal recording apparatus. The reason for this relatively high capacity is, of course, the very small effective distance between the two condenser charges. During the recording of the signals this condenser is continually charged and discharged, and the corresponding current must pass through the interior of the semi-conductor. Consequently, a very high internal resistance of the semiconductor will produce a certain lag in the charge and discharge of the electro-adhesion system and therefore also in the action of the apparatus, thus limiting the maximum recording speed attainable. The low internal resistance necessary for high-speed recording is, however, obtained by the chemical impregnation of the agate, and it was in fact only the introduction by the authors (in 1919) of the hollow agate cylinder containing electrolyte which made high-speed recording by electro-adhesion possible over any extended period.

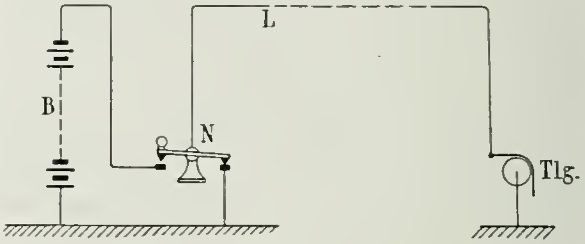


FIG. 9.

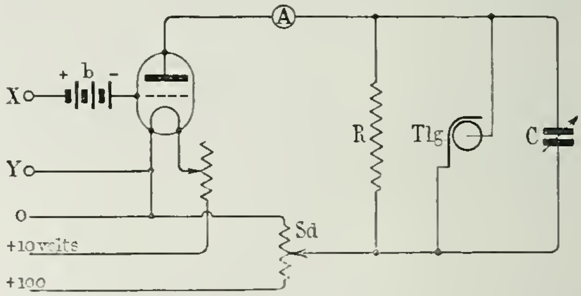


FIG. 10.

Experience shows that the total resistance (including the contact resistance) of the friction system must be reduced to about 650 000 ohms for the satisfactory recording of about 400 words per minute, the apparatus consuming under these circumstances a current of about $10^{-4}$ ampere at about 65 volts, and the contact area being about 1 square inch.

For use on ordinary telegraph lines the connections are usually as shown in Fig. 9. The transmitting key, N, can either supply E.M.F. to the line, L, from the battery, B, or connect the line with earth. At the receiving station one terminal of the apparatus is connected to the line and the other to earth. The earthing of the line at the transmitting station is very essential. If the line were simply disconnected from the battery during the pauses between the signals, the charge accumulated on the line would have to be discharged through the very high resistance of the apparatus, and this would require a considerable time. Even if the line has a negligible length and capacity, a considerable lag in the discharge of the friction system proper will be experienced if the line is completely interrupted, as the charge on the friction system in this case must pass through the large contact resistance of the system, whereas the charge has only to pass through the much smaller internal resistance of the semi-conductor if the discharge can take place through an external circuit. The latter is always the case if the apparatus is constantly shunted with a suitable external resistance, and thus the apparatus can, without any difficulties of the kind just mentioned, be operated in connection with a valve with an anode resistance, as illustrated in Fig. 10.

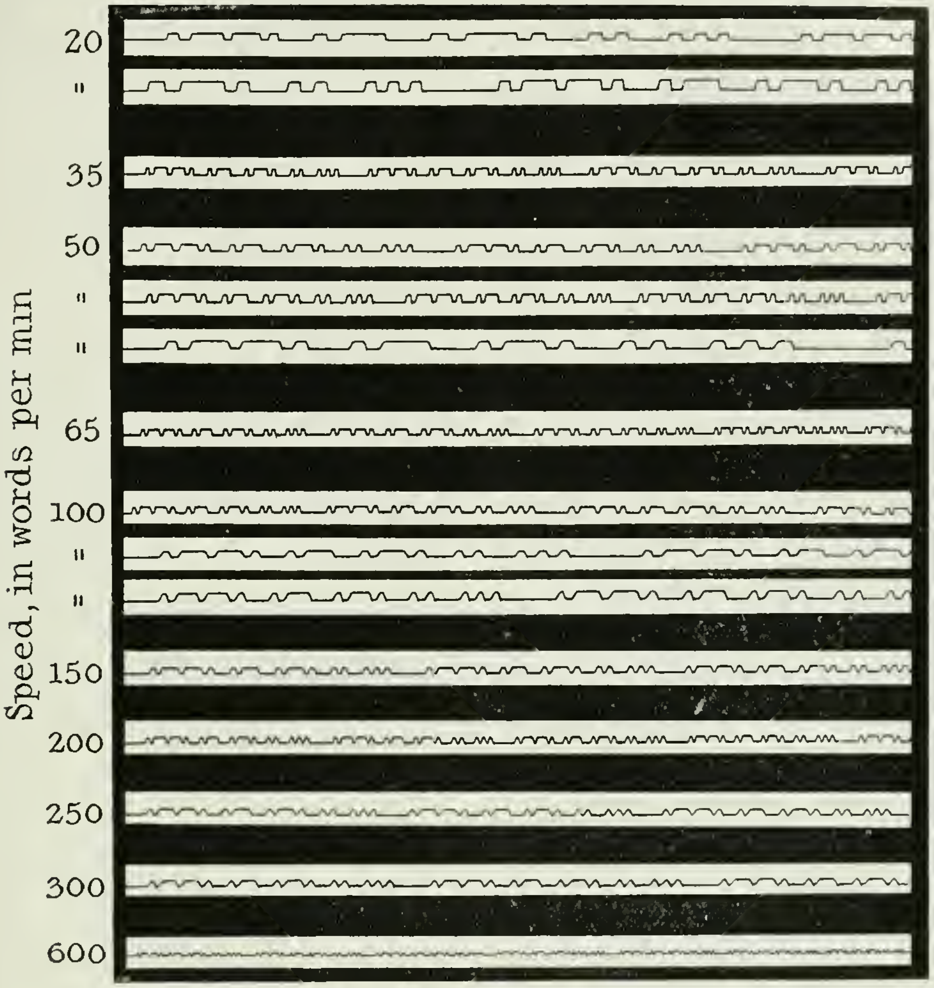


Fig. 11.

In this figure R is the anode resistance of the valve the high-tension supply to which can be regulated by means of the potentiometer, Sd. Tlg is the telegraph recorder. The telegraph impulses are applied to the terminals X and Y, which are connected with the grid and the filament respectively of the valve. The small battery, b, ensures that the grid is normally kept at a suitable negative potential relative to the filament terminal Y, X and Y being supposed connected. Normally, therefore, the anode current and consequently the drop of potential across R is very small, thus producing a negligible electro-adhesion in the telegraph receiver. If telegraph impulses of sufficient strength are applied between X and Y in such a way that the grid is made more positive during the signals, the drop of potential across R will increase sufficiently to operate the apparatus. This will also be the case if a sufficiently strong alternating E.M.F. is applied between X and Y,* the valve acting as a rectifier. Fig. 10 therefore represents the general diagram of connections for valve reception. If the valve is acting as a rectifier, the condenser, C, may be added in order to smooth out the fluctuations of the potential across R due to the alternating current, though the capacity of the electro-adhesion system proper is in many cases sufficient for this purpose. A very perfect rectification is by no means necessary for satisfactory reception, and a large capacity, C, will, on the other hand, reduce the maximum speed of reception, as will be readily understood.

The electro-adhesion telegraph is used with advantage for telegraphic reception at high speeds, and, on account of its small current consumption, in connection with high-resistance circuits (valve circuits included).

In Fig. 11 are shown samples of records obtained in a laboratory test direct from a transmitter, giving the standard word "Paris" at various speeds. The speed of the movement of the paper was varied somewhat for each sample, and therefore the space occupied by each symbol does not correspond to the speed (indicated on the scale in words per minute). The test was made with one of our early models having a comparatively heavy recording system (9 grammes), so that much better records can actually be obtained at the higher speeds. Even at the very high speed of 300 words per minute, however, the record is, as will be seen, quite satisfactory. The record at the extremely high speed of 600 words per minute was taken with the same apparatus, and can, in fact, be easily read. At present, however, such a high speed is of no value in practical telegraphy, though the extremely quick action of the apparatus may be found to be useful for some systems of telegraphic transmission of photographs.

If the electro-adhesion telegraph is connected with a small valve as generally used for radio reception, in the manner shown in Fig. 10, a recording speed of 300 words per minute is easily obtained without using a number of valves in parallel (or a very large valve) for the operation.* If radio signals are to be recorded, a sufficient amplification is necessary and in this case any ordinary amplifier may be inserted between the radio receiver and the terminals X and Y.

*Demonstration.*—The early telegraph model was shown in operation after the lecture, recording radio signals received on a temporary radio installation erected at the Institution building with the kind assistance of the Marconi Company.

### THE LOUD-SPEAKING TELEPHONE.

In Fig. 12, H, I and II is the electro-adhesion system, and f the spring holding the band, I, taut. The band is mechanically connected with the diaphragm of a sound-box L, either directly, as shown in the figure, or by means of a lever. The electric circuit consists of a battery B of about 70 volts in series with the secondary, S, of a telephone transformer, the primary, P, of which is connected with a microphone and a battery. The transformer has a high step-up ratio, so that the necessary high alternating E.M.F. is superimposed on the constant battery E.M.F. The latter forms the polarization E.M.F. necessary in all electrostatic telephones (and transmitters), which here, as is well known, plays the same rôle as the permanent magnetism in electromagnetic telephones. The use of a suitable polarization E.M.F., moreover, causes the apparatus to work on the steep part of the characteristic curve of the electro-adhesion system (cf. Fig. 5), where small variations of E.M.F. correspond to large variations of force, and where the curve can, within the limits of the force variation taking place during speech reproduction, be replaced approximately by a straight line, so that only negligible speech distortion occurs due to this cause.* It is obvious that the highest alternating E.M.F.'s occurring must be considerably smaller than the polarization E.M.F.

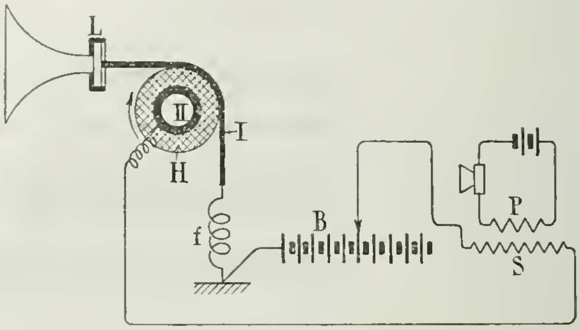


FIG. 12.

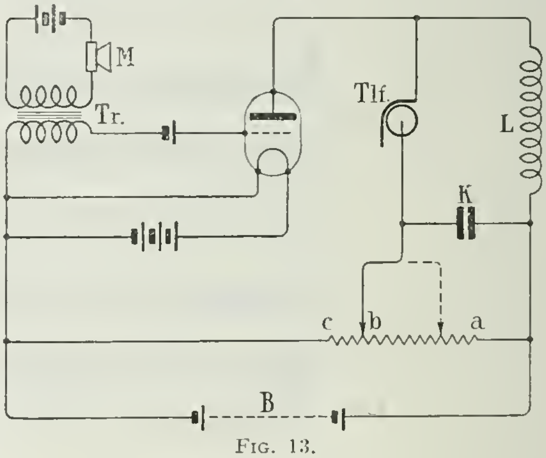


FIG. 13.

If the loud speaker is to be operated in connection with a thermionic tube, as for instance for the reproduction of radio-telephony, the circuit shown in Fig. 13 can be used with advantage.

---

* The ordinary anode resistance of about 100 000 ohms is amply sufficient for the discharge of the electro-adhesion system at this speed.

* The actual forces in the normal loud speaker with about 70 volts polarization E.M.F. are smaller than Fig. 5 seems to indicate, as a smaller band, encircling less than half of the cylinder circumference, is used for the loud speaker.

The battery, B, supplies both anode current to the tube and, by means of the potentiometer, a, b, c, polarization E.M.F. to the telephone. If the tube and the electro-adhesion system can be operated at the same E.M.F. (about 70 volts), the potentiometer can obviously be omitted. The transformer, Tr, fed from the microphone, M, is replaced by an inter-valve transformer if radio-telephony is being received. A large inductance, L (the primary of an inter-valve transformer is generally suitable), is inserted in the anode circuit, and the telephone, Tlf, may be regarded as being connected across this inductance in series with the part, ab, of the potentiometer. Thus the combination of the alternating E.M.F. across L and the polarization E.M.F. on ab is impressed on the telephone. K is a condenser shunting the alternating E.M.F.'s across "ab" and is only necessary if "ab" has a very high resistance. If no potentiometer is used, the telephone is simply connected between the filament and the anode of the tube, and K is omitted. The anode choke, L, is used with advantage instead of a transformer if the tube is of the ordinary small size. In this case it is not possible to increase the telephone potential by means of a step-up transformer, owing to the capacity of the electro-adhesion system.

As the capacity of the electro-adhesion system is connected in parallel with the inductance, L, resonance phenomena might be expected to occur at a certain frequency. If, however, L is a properly chosen iron-core inductance, no such effect will be observed in practice, and, moreover, both the internal resistance and the surface conductivity of the semi-conductor will assist in preventing any pronounced resonance effects.

Instead of a sound-box with horn, any other sound-reproducing device may be connected with the band of the friction system. The large mechanical forces developed by the electro-adhesion telephone permit of the application of large but comparatively rigid and heavy diaphragms, which will give very good reproduction without the use of a horn, which always produces some resonance effects.

*Demonstration.*—At the lecture a demonstration was given of a "speaking violin." An electro-adhesion telephone, in which the band was attached to the resonant body of a violin, the strings of which had been removed, reproduced violin music and speech transmitted from a microphone in a distant part of the building. As is well known, the violin body will resonate fairly equally over a very extended range of notes, including very high notes, and therefore music and speech are very well reproduced, the speech in particular being very clear and well articulated. As, however, the violin body adds harmonics to every simple oscillation imparted to it, the reproduction in each case exhibits some special "violin character." The timbre of the speech is therefore not reproduced quite faithfully, the reproduction of violin music being, on the other hand, of exceptional beauty, as the "violin character" is imparted once more to the music performed before the microphone.

The electro-adhesion telephone is capable of producing sound of great intensity without requiring the use of special power microphones or power valves; at the same time, the faithfulness of the reproduction is not surpassed by any loud-speaking apparatus hitherto existing. The authors have constructed a specially powerful model, in which the friction system actuates simultaneously a number of diaphragms; this model gives very good reproduction even at very high sound intensities at which electromagnetic telephones would be heavily overloaded and therefore exhibit considerable distortion.

The authors wish to express their indebtedness to the Technical College (Polyteknisk Læreanstalt), Copenhagen, and especially to the Principal of the Electrotechnical Laboratory, Professor Absalon Larsen, for the great kindness shown them during their many years' experimental work in the Laboratories of the College.

# CO-OPERATION BETWEEN THE ARCHITECT AND THE ELECTRICAL ENGINEER.

By Francis Hooper, F.R.I.B.A.

(*Paper received 26th February, and read at a Joint Meeting of* The Institution *and the* Royal Institute of British Architects *15th March*, 1923.)

"Science," the late Sir William Preece wrote in 1892, "is now advancing with giant strides. She has become the helpmate of man, and Science is but the knowledge of Nature, whose laws are the thoughts of God."

"As Science and Art are the chief instruments of modern civilization, so the engineer and the architect must work hand in hand."

It behoves all architects to voice the indebtedness of the community to the engineers who have already accomplished so much and are yet capable of vast and unexplored potentialities. Some will remember the delight felt when the cranked and wire-operated front-door bell was displaced by the electric gong; when the colza oil lamp, involving daily trimming, was surpassed; when the hand-power goods-lift was scrapped, together with the labour connected with the hand-bellows of the church organ.

### Some Present-day Uses of Electricity.

Electricity is to-day employed for lighting in positions and for purposes until recently unthought of: in street and workshop, study and operating theatre, in surgery and medical bath, in railway carriage, banker's strong-room, housewife's food store, palace and cottage, in places of worship and amusement, in picture and sculpture galleries, museums and schools, in flower gardens, in conservatories and winter gardens; in ventilation by exhaust or supply fans; in acoustics by means of telephone or wireless communication, thereby facilitating trade and business intercourse and efficiency, and yet all in infancy with undeveloped possibilities; in advertisement, enabling the salesman to exhibit favourably in his windows and showcases his goods to potential purchasers, as well as in the transport of passengers and goods; the engine driving machinery for the production of commodities and the refrigerating plant, for preserving perishable foodstuffs until required for consumption; synchronized time-pieces can be installed in the home, hotel, office-block or factory, adding much to efficiency and the saving of worry. X-rays, which have proved of such inestimable value to the surgeon and dentist in their work, are already used for the testing of steel and may, in all probability, be employed in connection with many other materials essential to the architect.

The generation and methods for distributing electrical energy do not concern us on this occasion beyond the desirability of urging that the present dependence upon coal should be regarded as temporary and only a stop-gap until replaceable powers become available, and that efforts might well be made to determine the most suitable voltage for general use, and that uniformity throughout the country might be sought to simplify the task of the important industries concerned in the manufacture of fittings and appliances.

Many topics might open wide fields for discussion, but the author will confine himself to a brief consideration of the following:—

(1) Lighting (diffused and concentrated),
(2) Heating and cooking,
(3) Ventilation and sound,

always bearing in mind that unemployment is most readily overcome by increased facilities for employment and that spiritual forces can only be invoked where the commonweal is in view.

### Lighting.

Innumerable sub-divisions would be required to classify the varied uses of artificial lighting, each needing specialized consideration; suffice it to generalize under two only, viz. diffused and concentrated.

Diffused lighting is required in the street, railway station, wharf, market, gymnasium, school, lecture hall, swimming bath, etc.

Concentrated lighting is required in the living room, bedroom, workroom, study, business house, museum, picture and sculpture gallery, warehouse, shop, theatre, concert hall, church, council room and mine.

Not only can lamps be fixed in new positions, visible or concealed, but they can also be controlled from a distance noiselessly and instantaneously, reflected and graduated, without impoverishing the air or risking fire—and even under water—unimpaired by wind, rain or lack of oxygen.

*Danger of glare.*—One important factor seems, however, at the present to require very special and earnest attention, as it affects comfort and economy and, hence, the popularity and usefulness of electric lighting. The danger of glare is one which concerns both old and young, the man in the street and the child in the school, the worker at the desk, the bench, the surgery, the pulpit as well as the pew.

In the last century candle-power was limited, and many present-day problems were unknown. Delightful was the small lamp or candle upon the writing-table, in the club reading-room, the choir-stall, the drawing-room, each fitting carefully suited to its purpose. To-day, too often, excessive candle-power dazzles, irritates and injures the eye and the brain alike, diffused glare destroying the restfulness and value of studied shade.

To-day some advertising agents, fiendishly regardless of self-respect and consideration for the public, have made vulgar some of our important streets and many of our open spaces. Upon this the public opinion needs education.

*Street lighting.*—Street lighting is being carefully and earnestly studied by many of our public authorities, and elevated central lamps in our thoroughfares have permitted the removal of the standards which, in crowded thoroughfares, needlessly reduced the capacity of our footways.

*Shop lighting.*—The lighting of shops is no unimportant matter to the public, as well as those who seek to display their wares. The advantage of the concealment of lamps behind screens has been successfully demonstrated by many, adding much to the attractiveness of the street and the prospects of business.

*Façade lighting.*—Much improvement is possible in lighting the outside of buildings of popular resort. The outlining of windows and cornices by lamps wholly destroys the value of an architect's work; whereas, diffused and concealed lighting from a distance may be both distinctive and dignified.

*Internal lighting.*—Internal lighting needs consideration on different lines. Concentration is, in many cases, of material importance. Whether in study or business house, museum, picture or sculpture gallery, place of worship or amusement, the principles of the theatre may well be entertained. Delightful is a building in which the sources of light are hidden, its direction focused, and the eye is allowed the relief and rest such as Nature affords in the shade of a spreading tree during a bright summer day.

*Pictures and sculpture.*—Many a home contains pictures, sculpture and other choice objects, too often forgotten or overlooked by both occupants and visitors. Rarely do we find objects lighted with studied consideration of the best point of view and their background. This comment applies equally to most of the costly memorials erected since the war, whether they be in the open or under cover; hence, after dark, they are lost sight of and their purpose nullified.

*Gardens.*—Public and private gardens, too, might be turned to good account by artificial lighting and enjoyed by the many workers, whose leisure during daylight is but too limited.

### Heating and Cooking.

Under this heading must be classified all electric radiators, fires and cooking appliances, which are now beyond the experimental stage and are presenting opportunities to the architect where electrical energy can be obtained economically. Many establishments must be within reach of water power still unemployed for the purpose of generation. The architect and the engineer should, however, never lose sight of the fact that neither of these provides automatically for the essential change of air in the apartment in which it is used, as is the case with the coal fire with its chimney, and careful provision must be made for efficient substitutes.

### Ventilation and Sound.

Exhaust and intake fans for promoting ventilation are of the greatest importance to the architect, enabling him to provide the movement and renovation of air with means of remote control, thus making it possible to meet and overcome variation of temperature or fluctuations in the number of occupants of an enclosed space. This has already served to permit the use of many buildings for purposes quite impossible in their absence.

### Mines, Telephony, Etc.

The lighting and ventilation of mines is beyond the direct scope of the architect, but, as a citizen, he cannot be indifferent to the welfare, health and safety of the workers upon whom depends the winning of so many daily necessaries.

Similarly the development of telephony and wireless communication are outside our range on this occasion, but the connection between ventilation and the study of sound may be less remote than is commonly supposed, for acoustic defects are reported to have been overcome by improved ventilation of buildings.

In conclusion, the health and well-being of the community are so much affected by our respective occupations and interests that I trust I have indicated, though most inadequately, some of the many directions in which co-operation of the architect and engineer in our several activities is both desirable and necessary.

[The discussion on this paper will be found on page 736.]

# CO-OPERATION BETWEEN THE ARCHITECT AND THE ELECTRICAL ENGINEER.

By J. W. Beauchamp, Member.

(*Paper received 26th February, and read at a Joint Meeting of* The Institution *and the* Royal Institute of British Architects *15th March*, 1923.)

Summary.

The object of this paper is to arouse discussion upon the relation between the architectural and electrical engineering professions, to explore the possibilities of closer joint working and means of keeping each profession advised of the needs and developments of the other in so far as they touch mutual and efficient working.

The service rendered by the electrical industry to the public is the result of combined working between at least three sections of that industry.

The rapid development of electricity in the field of heating and cooking is dealt with and also the factors determining the extent to which that medium can usefully be employed at different competing rates or prices for fuel, gas or electrical energy.

The varying restrictions and conditions covering electricity supply in different districts are considered, and also the modern movement towards simplified tariffs and methods of charging.

Suggestions are made as to the work of the architect in providing for the use of electricity in buildings and in allowing for extension, greater variety in use, and the arrangement of cables and ducts.

The influence of electricity on the design and cost of buildings and probable developments in the near future are also discussed.

The paper concludes with a suggestion that it should be possible, without interfering with the definite work of the architect, consulting engineer or contractor, to set up some joint body to act as *liaison* in regard to policy and the distribution of information between the two professions.

The prime object of Mr. Hooper and myself on this occasion being to promote a useful discussion, I am confining myself principally to the relations existing between the two professions, a few points on recent development, and to the expression of hopes which I think it should not be too difficult to realize with advantage to all of us.

In the last event the architect in all his work has in mind the occupant or ultimate user of the structure for which he is responsible. Similarly with us, the basis of all our work, scientific or commercial, lies in discovering the needs of the ultimate consumer of electricity and meeting them in a way which will give satisfaction.

Our work is perhaps a little complicated by the fact that the user of electricity depends upon three leading sections in our industry for his complete service.

The advantages of electricity need no bush in this place, but to enjoy them one must have the joint assistance at some stage or other of the supplier of electrical energy, the maker of electrical apparatus, and the contractor who installs and maintains it. We also seek the important assistance of the architect, consulting engineer, and other designers or advisers who at various stages may come between us and the final user.

I feel that in many cases the architect may not be brought so closely in touch with the several leading branches of the industry as is desirable, or he may not perhaps realize to how large an extent the final satisfaction of his client depends upon the co-operation of those several branches—if this is the case the blame does not lie with the architect but with the electrical industry for having in a general way neglected him.

I am aware that in many respects the modern architect is well up to date electrically; he can and does claim the assistance of the consulting engineer and of the electrical contractor, and the various manufacturing experts on illumination, heating, ventilation, etc., are only too anxious to serve him, but, after all, we are dealing with a line of scientific invention and with an industry which progresses at a very rapid rate, also one which is subject to widely varying conditions in different districts and countries. Applications of electricity which are commonplace in certain areas may, for the time being, be impossible and almost unknown in others; practice which is standard with some undertakings may still be regarded as only in an experimental stage by others, and for this reason we feel that something more should be done, if possible, to keep in touch with so important a colleague as the architect.

It is at least as necessary for the electrical industry to advise the leaders of other professions and industries as it is for the electrical industry to advise the public. So closely are we now entering into the field of work of the architect, the ventilating engineer, the works production manager, and all whose business it is to handle material or transport, that it is essential for experts in each of these branches to have some knowledge, wide if not deep, of electrical applications, and particularly essential that that knowledge should be kept up to date.

It has sometimes been our experience that after working up a desire for certain electrical applications on the part of the client, the business fails to mature owing to the opposition of his architect who, not perhaps familiar with our recent achievements in this particular direction, wishes to save his client from what he considers to be an experiment, but what we know to be a practical success under the particular conditions in question.

In the past perhaps some mystery has surrounded electricity and the electrical engineer. The magic has, however, passed; we want our appliances to be regarded as a superior kind of ironmongery or engineering material. We know precisely what we can do under different conditions and what the various operations will cost the user, although it would be bold to say what may be done in a few years, or to set any limit to progress.

The electrical profession desires that everyone outside it should get some practical working knowledge of electricity, its applications, and of the economics underlying its sale and use. Exhibitions and educational advertising work are doing much to accomplish this, and although it is some years since we have been able to hold a large Electrical Exhibition, yet in one sense all Exhibitions are electrical, so great is the use made of this medium in such displays. In 1924 we may expect to make a representative display of our latest work at Wembley, and, in the meantime, local shows, generally promoted by supply undertakings and contractors, have become more numerous and are always worthy of a visit, as they are supported by the principal manufacturers and, so far as their scope extends, usually exhibit the very latest appliances in action.

The increasing use of electricity will be one of the most important contributions to the solution of the smoke problem, bringing back sunshine to the cities and going far to reduce dust and noise.

The competitors of the electrical engineer reproach him with being a waster of fuel, at least where electricity is produced by a thermal process. He replies that the relatively low efficiency of his process of generation is offset by the extremely high return which the consumer obtains through electrical appliances for the energy put into them—but we begin to perceive that the matter goes further than that.

Mechanical power, artificial light and warmth obtained from the heat energy latent in combustibles have in their use generally been accompanied by gross waste—the labour and dirt inseparable from the older methods have been even unnecessarily great by reason of the lack of care in use and the needless inefficiency of most of the appliances employed.

In supplying heat energy in the form of electricity we offer something relatively more expensive yet easy to measure and control exactly, with the consequence that the user is encouraged to study problems of energy conversion in a way never possible before. Thus, he applies power directly to the machine, gets better illumination with less waste, and is able to produce heat exactly where most effective. The result is a steady revolution in methods, reaching now to the home and every department of life, and promising to reveal the electrical engineer as the great practical economist of the fuel and human energy hitherto so lavishly squandered.

Consideration of the relative cost of electricity, gas and fuel is too large a subject for treatment in a short paper, and is so modified by the circumstances of each case as to make generalization dangerous.

Information regarding costs for lighting and power work is general or easily obtainable, but it may not be out of place to indicate the range or limits of price effective in the application of electricity to certain other purposes.

The Board of Trade unit of electrical energy, or kilo-watt-hour (1⅓ horse-power-hours approximately), contains 3 411 B.Th.U., and 29 units of electricity contain 98 919 B.Th.U., i.e., say, 100 000 units or one therm. This is a physical relationship from which our gas friends delight to reason that gas at 10d. per therm is equivalent to electricity at ⅓d. a unit.

However, many prefer electricity to gas at rates up to:—

8d. and 10d. per unit for lighting.
3d. and 4d. per unit for small heating and power appliances.
1d. and 1½d. per unit for general cookery and fires.

So it becomes obvious that the heat content of the unit of gas or electricity is by itself no sufficient measure of service rendered; the efficiency with which the users' appliances convert this heating value into effective light, warmth, cookery or power being the principal deciding factor, further modified by considerations of speed, convenience and cleanliness.

Taking parcels of coal, gas and electricity of equal heat-energy content, performance in practical use is apt to be of the following order :—

| | Coal | Gas | Electricity |
|---|---|---|---|
| | % | % | % |
| Potential heat value | 100 | 100 | 100 |
| Effective heat value (fires) .. .. | 10 to 25 | 40 to 60 | 100 |
| Effective cookery value : | | | |
| Ovens .. .. | 5 to 10 | 20 to 40 | 65 to 75 |
| Boiling plates .. | ? | 30 to 40 | 50 to 60 |
| Kettles .. | ? | — | 80 to 90 |

The tabulated figures represent approximately the efficiencies of conversion in the appliances used in each case.

Users will pay more for electrical energy than for any of the competing services, and how much they will pay depends upon many variables, the object to which the electricity is to be applied, the wealth of the consumer, his views on the value of comfort and cleanliness, etc.

There are processes in industry where the cost of power is so important a percentage of the total cost of production that closely competitive rates must be secured. There are others where it is so small that the rate per unit is of little importance compared with the value of a flexible, clean and reliable source of power.

Similarly in the house, cases are met with where the wealth of the householder may be such as to make him impervious to suggestions for reducing his staff or improving conditions in the working part of his establishment. These cases are becoming fewer, and most householders to-day are willing to listen to proposals for mechanizing their kitchens and domestic offices, cutting down staff or giving it less excuse for dissatisfaction.

There are houses where half-a-dozen fires are kept burning all day for six months of the year, and where the kitchen range alone has been found to account for half a ton of coal per week. Not many, perhaps, of these are left now, but they are excellent fields for electrification.

Broadly, however, our great prospect lies with the middle classes, the dweller in the villa and the flat. In the wide range of homes supported by incomes of, say, three or four hundreds a year up to as many thousands, economy is important in varying degree, but there is usually willingness to spend reasonably for some extra comfort or simplification and the means of making housekeeping less of a trial.

In dealing with this class of work we suggest careful consideration for the combination of fuel and electricity, confining the burning of coal or coke to one, two or perhaps three points, and using electricity for all occasional or short-hour heating, for cookery, suction cleaning or other work of that kind to which mechanical power can be applied.

It is difficult to lay down the law as to competitive rates for electricity, fuel or gas, but the following broad statement may help to define limits and lead to further investigation as each case arises.

Electric lighting gives complete satisfaction at all rates up to 10d. or 1s. per unit, these figures being relatively high to-day and bettered in most areas.

For occasional or short-hour heating, and for the regular or all-the-year-round cookery of food, rates of 1d. to 2d. per unit against gas at 4s. to 5s. per thousand feet (usual calorific values) give satisfaction. Roughly one may say that the price per unit may range from one-sixth to one-twelfth of the price per therm.

For small-power drives or heating appliances, fans, flat irons, suction cleaners, kettles and detail cookery apparatus, considerably higher rates will generally give complete satisfaction, owing to the convenience of these devices and because they account for but a small amount of electricity in the course of a year.

The above figures are a rough guide to comparative values, electricity in terms of gas; there are other considerations which may make or mar some of this business.

In some classes of property the more expensive pieces of apparatus have to be let out on hire. Again, their free or limited use may depend a good deal upon the wiring installations being provided with convenient outlets for connection, etc.

It may be of interest to consider probable expenditure upon electricity in a middle-class house, taking a house inhabited by the more or less standard family, five or six persons, say three adults and two or three children, pre-war value of the house £35 to £70 per annum.

Lighting consumption 200 to 300 units in the year at 7d. per unit, say £7 per annum.

Cookery, regular, on electric range: 1 unit per head per day = 350 × 5 = 1 750 units in the year, at 1¼d. per unit, say £9 (or 3s. 8d. per week).

If in this case electricity is used only for small apparatus it will be seen that about 2 units a day becomes available to the consumer for an addition of only 50 per cent to his lighting account, and this would cover the regular use of a flat iron, suction cleaner, washing machine and kettle or small utensils.

### ELECTRICITY SUPPLY.

*Variation in conditions.*—The rates charged for electricity, the nature of the tariffs in force, and even the development of the electrical contracting business vary a good deal between one district and another. These conditions are, however, improving and there is a strong tendency towards more elastic and simpler forms of tariff, the hiring-out of certain classes of apparatus, and the reduction of restrictions in regard to service connections and incidental charges.

To an architect operating from time to time in different districts it must be confusing and difficult to understand the differences which exist. For example, electricity is sold for lighting at anything from 4½d. to 1s. a unit, whilst in some parts electric cookery goes ahead briskly at 1d. or 1½d. a unit and in others is prevented from developing at all by rates as high as 3d. or 4d. a unit.

The reason for these differences is bound up with the history of the electric supply industry. Some of the undertakings operating for many years in areas where business has been confined to lighting have not been able to develop or to replace machinery quickly; others stimulated by a big industrial demand have been able to install plant of increasing size and greater efficiency every few years.

The widely varying magnitude of generating plants and supply networks means that in some places almost any new business can be tackled with ease, whilst in others some electrical developments may be embarrassing rather than desirable. On this account it is not safe to generalize from limited details or experience; uses of electricity impossible to recommend in one area may be practicable and cheap in another.

*Tariff for electricity supply.*—Methods of charging for electrical energy are about as numerous as there are engineers in the supply industry, because although a number have refrained from inventing new tariffs some of the more active are responsible for a dozen or so.

However, this work has not been in vain; it has led to very close investigation into the costs of production and the possibility of charging in various ways so as to encourage the use of electricity to develop in directions likely to result in cheapening the supply. To-day there is a crystallization of ideas towards methods of charging which call for some annual or periodic fixed payment in relation to the size of the house or the capacity of the apparatus in use, and in addition to this charge to sell the electricity in any quantity and for any purpose at a single and low rate per unit. The method is promising and has become rather general in large power work; in less precise but simpler forms it will spread rapidly for domestic uses.

The subscription or periodic charge is generally calculated to return to the supply undertaking those expenses incurred in maintaining the supply demanded by the consumer, expenses to a great extent unaffected by the amount of electricity he uses. These charges have been based upon the electrical capacity of the apparatus in use, or some percentage of it, or they may be calculated upon the assessment of the premises, the number of rooms or floor area, but the object in all cases is to obtain from the user a reasonable payment over the year in accordance with his normal use of the supply and then to be in a position to encourage further and wider use by selling electrical energy for any purpose at a low and uniform rate per unit.

The increased efficiency of the electric lamp and of electric lighting methods has made it difficult to deal equitably with all consumers, large and small, merely by selling units at a flat rate.

### LIGHTING.

Out of the work of the electric lamp maker has arisen the modern science of illuminating engineering. The ability to obtain powerful and concentrated light sources comparatively unaccompanied by heat has enabled lighting problems to be approached in a scientific manner and optical or decorative needs to be given full scope.

The architects have assisted in the work of the Illuminating Engineering Society, and are acquainted with the researches made by that body into the lighting of schools, public buildings, cinemas, etc., all of great value, leading to economy, protection of eyesight, and a better public understanding of good lighting.

A recent example of this work is found in the investigations made into the lighting of the Ministry of Pensions building, where a by no means indifferent lighting installation was altered to give much more effective results with an important decrease in running cost. The National Physical Laboratory has carried out experiments in lighting in specially constructed rooms, exploring the features necessary for good illumination.

There is room for the closest collaboration between the architect, the electrical contractor and the illuminating expert, and the help of the architect is the more welcome as in this work we have so often to make some compromise between scientific perfection and the taste and desire of the client, who must, as a buyer, be guided rather than forced towards better methods.

*Electric light and eyesight.*—In an age when much scientific information is scattered about one must expect to find occasional examples of its being somewhat ill-digested ; quite recently we have seen public attention drawn to the alleged danger of electric lighting to eyesight.

The effect of the modern electric lamp on the eye has been described as the "whip lash," although it is only fair to say that that expression was used by one responsible for the production of some very bright lighting of another sort.

The electrical industry produces lamps, shades and fittings correct in every respect, but cannot always control those who fit them up, and it is necessary to work consistently towards educating the people in the wise use of the powerful lamps of to-day. It is useless to tell people that they do not need such powerful light sources; there is a sort of greed for brilliant artificial lighting, even in countries more favoured with sunlight than ours.

It may be worth while to state here quite definitely that there is nothing to fear from ultra-violet, X- or other non-lighting rays which have been said to be given off by electric lamps. Practically speaking, all these emanations are checked by the glass of the bulb, and the danger is merely one of glare, produced by the use of bright naked lamps of any kind if placed in the line of sight. Correct height, spacing and shading of electric lamps remove all trouble of this kind and can be made to result in an effective illumination which actually preserves the eyesight under the severe strain put upon it by close work and long hours of artificial lighting which are a feature of modern life.

*Indirect lighting.*—To a great extent the economies offered by improvements in electric lamps have been taken up by an increased standard of lighting, and by more indirect methods of use. The relatively low cost and the incidental economies of electricity now make it possible to consider something more than the bare lighting needs and to introduce decorative features of great value. For example, reflected or indirect illumination, beautiful as it is, suffers from a certain monotony and lack of shadow or contrast, which, although useful in drawing offices, works and large buildings, may for domestic use need to be mixed with direct lighting in order to get a pleasing mixture of light and shade. The decorative wall bracket, and a variety of ornamental fittings with small lamps, can be employed with regard to appearance rather than scientific illumination and without fear of unduly increasing the cost.

Proper contrast in lighting aids mental concentration, and experiment has shown that the best practice for school, desk work and factories is to provide reasonable and well-diffused general lighting, so as to prevent accident and facilitate movement, and in addition to this to allow the eye to work in a strong directed light on blackboard or tools.

The architect is also interested in the growing use of flood lighting, first employed with the object of throwing up the features of fine buildings, and now being extended to the lighting of poster hoardings and similar work. This can be very useful and is less troublesome than the older methods of outside decorative lighting, whilst for business purposes it has that mixture of dignity and impudence which appears to be the foundation of modern publicity work.

*Church lighting.*—In the lighting of churches we need the help of the architect very much. A good deal of excellent work has been done by the illuminating engineer, but, broadly speaking, the lighting of places of worship is bad, the standard is too low for reading, and the method is unfavourable to concentration. Latterly there has been a tendency to introduce some little dramatic element into this work, using concealed sources of light to throw up the features of the building and focus the attention of a congregation.

As an example of the interest of the engineer in problems of this sort, the following notes on "Church Lighting," kindly forwarded to the author by Mr. H. J. Cash are included in this paper :—

"A system of bracket lights should be used on the east side of the columns or beams, with reflectors arranged to throw the light forward and downward, so that each member of the congregation receives light from above and behind and is unable to see any source of light except by turning round. This secures complete absence of glare, there being no bright points in the range of vision of the congregation, yet ample shadow effect for comfort.

"Relatively brighter lighting of the chancel and altar should be provided without reducing the lighting of the main body of the church in order to obtain this desirable contrast.

"There is a saving in cost of the lamp fittings which, being small and inconspicuous if not entirely hidden, have not to be designed to harmonize with architectural features.

"In each of the cases which I have handled a rather unlooked-for effect has been obtained, the decorative parts of the altar and east end of the chancel having been thrown up and illuminated as never before. The reason for this is simple: the angle of reflection of light being equal to the angle of incidence, and direct sunlight entering during daytime services only through south windows, it follows that sunlight reflected from decorations of the east wall of the chancel can only reach the eyes of the people situated to the north of the church, a few of the clergy and choir perhaps.

"In the evenings and where there is a west window, and then only on few occasions, can direct sunlight falling on the altar and east wall of the chancel be reflected well down into the main body of the church; but by means of judiciously placed electric lamps this effect of reflected western sunlight, often very beautiful, can be artificially produced by day or night, provided that there is not a large number of strong lighting units intervening between the observer and the object illuminated."

## HEATING.

The growing use of electricity as a means of artificial heating is still little realized in many quarters. In approaching the public one of the difficulties is that they regard electricity as performing its various duties without giving off heat—largely our own fault. In the early days of electric lighting we found one of the advantages of electric light to be its coolness, making possible illumination work of a character which could not be accomplished by any flame-lighting medium, and so the idea has spread that electricity is not associated with heat.

It has now to be made clear that electricity is a form of energy which can be converted into heat with peculiar ease, given reasonable rates for the supply as already exist in many places. It offers the most perfect method of warming the air, heating solids or liquids, cooking food, and carrying out many artificial heating tasks in industry. The end of this work is not even in sight. New methods enable energy to be stored in the form of heated water or heated solid materials, and will give us a large proportion of the artificial heating work of the world because these storage methods make it possible to take electrical energy at times when it is cheapest and most convenient for the supply undertakings to deliver it and store it in the form of heat against the time when the consumer may need it.

In heating work the earlier experiences with electric power are repeated. The ability to control and measure electrical energy with great accuracy is bringing in its train important changes, introducing new methods of applying heat, fresh ways of preparing food, and doing a great deal to cut out the waste which in the past was so serious in the production of mechanical power, and has always been particularly so in the use of artificial heat.

The general user of artificial heat has no clear notions of quantity of heat. Difference of temperature is appreciated, but the actual cost and value of heat is understood by few, and even with present methods probably one-half of the fuel employed in the world could be saved provided sufficient care were exercised on the part of the individual user. Such care will not be given, although the increase in the cost of fuel has brought about some improvement, generally by the introduction of fresh and more or less expensive apparatus of higher efficiency and not by more care on the part of the individual user.

The electric method promises great help in this direction because it permits economy to be practised without calling upon the user for that exercise of thought which is so irksome to people when it concerns the routine affairs of daily life.

*Heating fallacies.*—The electrical industry of this country has grown up under conditions which naturally offered to it a very severe competition, namely, densely populated industrial areas in which the distribution of gas, and even of raw fuel, is a simple matter. The first big movement of electricity may be said to have started 15 to 20 years ago when a distinct advance was made in the use of electric power, that being at a time when the gas industry of the country was nearly 100 years old and thoroughly established.

The older competitors, fuel and gas, have never urged that their services were in any sense better than electricity, and in recent times they have given us credit to the contrary, from the first consistently keeping to statements on cost, maintaining that electric lighting was many times more expensive than gas; similarly at a later stage, but with signs of diminishing conviction, concerning electric power, and to-day carrying the same line of argument against electric heating. Here not only may they have more ground for argument, but they also pursue it with the more vigour because they regard heating as being their special province and, having to no small degree lost the lighting and power business, naturally try to retain the heating.

It arises from these conditions that we have all been well sprinkled with propaganda and argument concerning the relative heat value of fuel, gas and electricity, the arguments generally being based upon the thermal efficiency of the several chains of generating process, electricity being, according to our competitors, out of court because so large a percentage of the heat energy in the fuel from which it is generated is lost in the first stage at the power station.

The theoretical reply lies in the high efficiency of conversion of electricity back into heat in the consumers' apparatus, but the electrical engineer discovers in practice that many other considerations apply which place him in an even stronger position relatively to coal and gas. Thus, not only with electricity as a carrier is heat energy used more efficiently by the consumer, but apparently he is able to do with a great deal less of it. Space forbids enlarging upon this, but the subject of the quantitative relationships of heat and of the methods, radiant or convective, to be employed is of great interest, and it is already obvious from experience that one must not generalize solely from theoretical considerations.

The warming of people using a room for a short time by means of a centrally placed electric radiant fire, as for example under the table, may be more effective with a small consumption of electricity than with a considerable coal or gas fire in the usual and less effective position on the hearth.

The question of interest to each member of the public is not the cost or consumption of fuel alone ; but the help or service he can obtain and the medium which will give the least trouble and best results, and either produce the least inflation or the most deflation of his total annual expenditure.

It is not sufficient to compare the cost of this or that form of power or heat, but, as in many other cases, one must consider the effect of a new method on total expenditure, volume of output or quality. The problems of the factory are reproduced in the home, where they do not differ appreciably in kind but only in degree.

The combination of electricity and other methods of heating is of interest, a mixture of the usual coke-fired hot-water heating system with a moderate provision of electricity in addition for radiant heating is likely to be very useful in large buildings, and not only give the occupants more cheerful heating and better control of temperature but also enable the furnace to be worked at a uniform and economical rate.

Ovens or other cookery equipment have been made for partial heating by the flue gases of anthracite or coke furnaces, the final cooking temperature being provided for by a limited use of electric elements.

Attention has been given to the wider use of the waste heat from electric generating stations in the form of steam or hot water, and particularly in congested districts it seems likely that a good deal may be done in this direction by working around the sound principle of using the cheap and inferior carrier of heat energy, fuel, for heavy heating work and the more expensive but far more controllable carrier of heat energy, electricity, for the finishing off, final adjustment of temperature, and the precise treatment of food or any substance to be treated.

We have a parallel in the treatment of steel and certain other metals where " pre-heating " is carried out with fuel and the final melting done by electrical means.

### Power.

In the supply of power the electrical engineer meets but little competition, at least until large powers and long hours of use are involved, with the exception of building operations where motors of considerable size may be employed. The architect is more particularly interested in the use of power on a small scale as for lifts, central vacuum cleaning-plants, ventilation, etc., but recent years have increased the scope of the small electric motor, and even in the home its use for portable suction cleaners and for washing and other light machinery is extending. It calls perhaps for little attention in house design beyond suitable provision being made when the wiring is carried out, but the result of " mechanizing " the housework may well be to give the designer more freedom, and certainly all electrical applications help the decorator by encouraging an increased expenditure in view of the longer life and more enduring freshness of furnishings where dirt is reduced by the partial suppression of fires and by cleaner methods of removing dust and carrying out other household tasks.

### Cookery.

Where electric supply conditions permit the regular cookery of food by electrical means, the fullest advantage should be taken of the method. A more convenient arrangement of kitchen and offices becomes possible when the range need no longer be located near a chimney but can be placed where convenient for natural light and in relation to dressers and sinks and the other equipment of which it is so important a part. Electricity in the kitchen, even if associated with the use of fuel for water heating, allows most compact arrangement, reduces fuel storage space and puts the principal office of the home on quite a different level in regard to cleanliness and ease of working.

In converting old and large houses into flats the value of electricity becomes very apparent, making possible arrangements which could not be carried out with any other means of heating.

*Commercial cookery.*—The choice of cookery method in canteens, hotels and restaurants is of considerable importance to the architect responsible for their construction. As in the home, electric cooking gives greater freedom in design, but also often saves space and labour in this class of work to a degree which results in a large saving in running expenses, even making it possible to employ premises which with other heating media would not be suitable for the work at all.

Some of our largest hotels have for many years, either through public supply or by means of their own generating plant, depended upon the combination of electricity and fuel for all their requirements. There is a tendency for these great organizations to become more and more self-supporting and to put in equipment enabling them to carry out the whole of the cookery, even to the making of bread, the operating of their own laundry, sewing rooms and repair workshops, and so to become self-contained, like little towns under one roof.

### The Storage of Energy.

The difficulty of storing electrical energy can to some extent be overcome by converting it into heat, in which form it can be accumulated over short periods without serious loss.

This principle is being developed particularly for the heating of water. Already much progress has been made in countries where coal is scarce and water power abundant, and even here the prospect of selling electrical energy during the night, when its cost of production is not much beyond the expenditure on fuel, is attractive to the electrical supply undertakings, whilst the ability of obtaining hot-water storage tanks suitable for the bathroom, scullery or lavatory introduces problems of interest in house building. Given the right material and sufficiently low rates, the appliances would be installed at the points where the hot water is required, so that internal pipe work would be limited to cold-water supply, the heat losses and other inconveniences of hot-water delivery piping being avoided.

### Private Plant.

In country-house installations the use of electricity has generally been limited to lighting, and in a broad way it may hardly be defensible to put in machinery with the object of turning oil or fuel into electricity which will immediately be turned back into heat. But one must remember that the user of electricity is apt to demand more and more applications, owing to its cleanliness and convenience, so it is generally worth while in private plants to provide at least for some of the small conveniences such as flat irons, fans, kettles, small fires, suction cleaners, and things of that kind. For this reason one should exercise discretion in installing plant only just capable of meeting the first demands or putting in generators of low voltage, which, though satisfactory for lighting and perhaps simplifying the wiring systems, have the disadvantage that they make it almost impossible to use electricity for any other purpose.

In some of the larger country-house installations one has also to provide for the home farm, and here again a few spare horse-power may be most valuable and enable substantial economies to be effected in labour.

When putting in a plant to be driven by water power, even if the power is only sufficient for the maximum lighting it is generally available throughout the 24 hours, and with modern appliances much of the waste energy can be turned to effective service in the form of water heating and so be of great use to the householder, reducing his expenditure upon fuel and cutting out a good deal of work and dirt.

### Lifts.

The architect has hardly followed up the advantages of the electric lift as rapidly as he might have done, and in many instances he still provides a handsome and capacious staircase whilst putting the lift in some more or less out-of-the-way position to which people have to crowd, perhaps through dark and inconvenient passages, before they can use it.

Naturally the designer is reluctant to lose the decorative possibilities of the staircase; but where buildings are erected for utility rather than ornament it appears that the time has come for the staircase to take its proper place as an alternative or emergency means of moving from floor to floor, and attention should be concentrated more upon the lift and particularly upon the approaches to it and its position in the building.

In many cases its advantages and conveniences are unnecessarily discounted by difficulty of ingress and exit, with the consequence that the young still use the stairs for short distances to an unnecessary extent and so defeat to a certain extent the object of the lift builder.

### Building Work.

The use of electricity in building operations is too well known to the civil engineering section of this audience to be worth more than a passing reference. Here the actual cost of the energy is generally a small matter; the lighting of building-works all night without danger, operating cranes without the use of fire and inefficient steam engines, handling fuel or ashes and similar employment of this form of power on constructional machinery have become common practice amongst builders where power supplies are available.

The employment of electric welding and rivet-heating are less well known, but already we have examples of electrically welded steel roofs, and have shown the superiority of this method of heating rivets for constructional steel work. Further advance in these methods will offer many opportunities for change in design and building practice.

In engineering work we have to give careful consideration to the relation between the delicacy of any item of plant and the ease or difficulty with which it can be got at for adjustment, repair or renewal. The practice here is generally evolved slowly by experience; for instance in the motor car, where the makers produce designs which permit an easier access to parts wanting frequent attention than to those which last more or less for ever. As we introduce more engineering material into buildings, these considerations also require attention.

A simple but perhaps not bad illustration may be found in connection with the electric bell. The circuits generally consist of thin and rather frail wires laid under floors or in zinc tubes under plaster. If laid properly they are practically imperishable, but should they fail or be damaged by subsequent work in the house it is often easier to run a new circuit than to attempt to get at the existing ones.

Recently the occupant of offices at the top of a large block of buildings desired to put in electric fires; he was satisfied with the cost in use and willing to pay for the necessary circuit or wiring required. His proposal was, however, refused by the landlord, who considered that there were already too many wires in the place and on the staircase, meaning of course that the installation was a complete muddle which had grown up piece by piece in the course of many years and in a building where no provision had originally been made for the accommodation of the wires and cables, so adding to the expense of everyone who wanted electrical apparatus, and certainly not adding to safety.

The question of providing not only for electric circuits and the connection of apparatus but also for the steady extension of their use is an important one, and should be taken into consideration not only in new buildings but in renovating or altering old ones.

In the house alone we have to-day wiring and cables for lighting, heating, cooking, portable apparatus like suction cleaners, electric bells, often enough telephones between one room and another, and now the connection of radio aerials, and so on.

Ducts or openings through all walls leading from room to passage or room to stairs could be provided with great advantage; they would be easily plugged until needed and allow all sorts of extension work to be carried out with ease.

In certain flats to be built in an area where electricity is cheap it is proposed to run massive copper bars up the stair wells, these being fixed in chases and tapped to each flat with a capacity proper for lighting, cookers and some of the heating needs.

A matter of importance to the development of electricity in the home is the provision of ample connections for the operation of portable appliances, generally known in the industry as "outlets."

Many small appliances are sold for operation from a lampholder, and quite a lot of good work is done in that way, but the method is not ideal. The lampholder will only supply apparatus of relatively small capacity, like the fan or flat iron. Often it is not convenient to use it; it may mean the removal of the lamp, causing trouble or breakage, or in a room where there is only one lighting point fitted it may mean that the appliance cannot be employed after dusk.

The really satisfactory solution is to provide one or more plug outlets in each room. This is an immense help to the householder. He can from time to time buy and use fresh pieces of apparatus without any preoccupation as to whether he will be able to connect them up, or if he will have to pay for extra wiring.

These outlets and, in fact, all accessories should be specified to be British Engineering Standards, or at least to comply with the dimensions provided in those Standard Specifications, so that interchangeability is secured. The architect can help very much in this important matter.

I have little doubt that it will be agreed that in much work the workmanship is more important than the system employed; the indifferent worker may make a bad job of the best wiring system, whilst the factor of safety of all electrical material is so high that really good craftsmanship will make a satisfactory installation out of the simplest materials.

The electrical contractor is looking with renewed interest now to apprenticeship; his Association is taking an interest in the education of its workers, and has the support of their trade union in this matter. Movement in this direction, coupled with a scheme for registering the electrical contractor similarly to the plumber or sanitary worker, will do much to raise the standard of installation work.

The I.E.E. Wiring Rules are at the present time being amended. So complex has the industry become that one can hardly hope that the Rules may be reduced in length, but they will, so far as possible, be simplified, and it may perhaps be no indiscretion to suggest that future editions will, perhaps, contain some element of "grading," making it possible, whilst providing for good work in all cases, yet to demand conditions less onerous in small buildings than in those where the responsibilities of the electricity supply are greater.

It has been argued that the time has arrived for more detailed methods of planning and estimating for electrical work, and that, at least in large jobs, the consulting engineer and electrical quantity surveyor could more often be employed by architects with advantage, and a more comprehensive attempt made to lay out the electrical work in advance and to offer to competing firms a clearer lead to the requirements than is at present usual, so enabling quotations to be reduced to a more common basis.

### CONCLUSION.

In conclusion the author would venture to suggest for the consideration of the architects that it might be possible to form some permanent *liaison* between their Associations and the Associations of the electrical industry, perhaps a joint Committee drawn from the Councils of the several Associations and sitting at intervals to examine and ventilate any proposals put forward by either side.

It is not suggested that this Committee should give technical advice or do any of the work now done, and properly done, between the architectural and electrical professions by the employment of consulting engineers, contractors or manufacturers, but that the Committee should deal more particularly with questions of policy, or possibly propaganda, between the two professions and with questions as between, for example, the electric supply industry, the architect and the consumer. Such a Committee could take a very independent line and could advise architects whether conditions in a particular place were favourable or not to this or that application of electricity, and in many ways assist them with unbiased guidance, leaving them to the usual sources for all detailed information and help.

Out of such a Committee might arise some method for instructing architectural students in electrical matters up to a certain point, as, for instance, providing them with lectures on the economics of electricity supply, giving the young architect a clear, though perhaps superficial, view of the conditions which govern the sale, purchase and use of electricity, and leading him to recognize the need for more detailed study of the subject.

The author would express the hope that in discussion we may hear of our faults as the architect sees them. It is impossible to be too frank in this direction; practice and conditions vary greatly in different districts, and we are only too well aware that business is often checked in forward areas by the client's or architect's experience of restrictions in some other place where working conditions have not allowed a progressive policy to be pursued.

In preparing this paper the author has drawn upon the records of the British Electrical Development Association, and would particularly acknowledge his indebtedness to Mr. H. J. Cash for assistance and many useful points in connection with installation work.

## DISCUSSION ON THE PAPERS BY MR. HOOPER AND MR. BEAUCHAMP READ AT A JOINT MEETING OF THE INSTITUTION AND THE ROYAL INSTITUTE OF BRITISH ARCHITECTS, 15 MARCH, 1923.

**Mr. F. H. Masters :** If we are going to reach that stage of electrical development which we all hope for, it will not be a matter for the electrical engineer alone or for the architect alone ; it is going to be a matter for the two in combination. To say that the architect does not know his business is as untrue as to say that the electrical engineer does not know his ; the difficulty is that they do not know each other's. From that point of view Mr. Hooper's paper is disappointing, for though he tells us a great deal about electrical matters he does not tell us how electrical engineers can help the architect in those details of our respective occupations which have so important a bearing on the health and well-being of the community. I should like to call the attention of the architects present to what Mr. Beauchamp says about the relative merits of gas and electricity for domestic purposes, and especially to his remarks under the heading of " Heating Fallacies." The question for both architects and electrical engineers is : Is it better to pay a little more and get something much more flexible and efficient, or to continue to put up with present inconvenience for the sake of saving a little, if indeed we save anything at all ? We have been told that one of the greatest needs of the country is houses. Electrical engineers think that one of the greatest needs of the country is a house in which electricity can be used to the greatest possible extent. I live in a district where a large number of middle-class houses are being built, the sort of houses where electricity ought to be used, and for various reasons could very easily be used ; yet the electrical installation in nearly all these houses consists of one, or sometimes two, lighting points in each room, and, as a concession to modern thought and practice, one wall-plug per house. I submit that that is not enough. I think that in each living room and each bedroom there should be at least two plugs ; one with a capacity of 15 A, and the other with a capacity of 5 A. In any district where a two-rate tariff is available these can easily be made, for wiring purposes, one point. If such an arrangement is made a maximum of electrical apparatus can be used very easily. The plugs and sockets should be standard throughout the house. To the 5-A plug can be connected kettles, toasters, irons, and so on, and, to the other, fires, suction cleaners, etc. This ideal—for, unfortunately, it is still an ideal—can easily be attained if both architect and electrical engineer collaborate from the beginning.

**Mr. A. H. Dykes :** This paper reminds me of the occasion, some 25 years ago, when my firm was first retained by the Commercial Union Insurance Company to advise on the electrical requirements of their new building in Cornhill. We had to collaborate on that occasion with an eminent architect, the late Mr. McVicar Anderson. He suggested that an improvement on the wood casing method of wiring should be made. My partner and I suggested that iron pipes should be fitted in the walls, and designed a system of cast-iron draw-through and outlet boxes which we had made for us by Messrs. Hayward-Tyler, a well-known firm of water engineers. It seems an obvious thing now, but at that time it was novel. The system has proved very satisfactory, and has scarcely been altered at all. Incidentally, we collaborated with Mr. McVicar Anderson in nearly all the fine buildings which he designed A year or so after that we used exactly the same method, employing the same contractors and the same cable, for the new Cotton Exchange at Liverpool, and we had trouble ; the wires broke down. We thought that there must be something wrong with the cable, but breakdowns still occurred when that was changed. In the light of our present knowledge, the reason for this failure is very simple ; it was due to condensation. The building was warmed to a very high temperature during the week, but on Saturday and Sunday it cooled, and the moisture in the damp air coming in from the river condensed in the pipes. One remedy which suggested itself was to employ a metal which would quickly attain the same temperature as the air, so that moisture would not deposit on it. We therefore put the cables in brass tubes. The system was afterwards extensively used ; for the wiring of the Institution buildings themselves, and for Waterloo Station, amongst others, under the name of " Kalkos." In a building in which condensation is to be feared perfect safety may be ensured by enclosing the wires in brass tubing and preventing too rapid an air flow by putting the switches in closed air-tight boxes. There have been many changes since those early days. Buildings then had solid walls and there was plenty of room between the floor boards and the iron girders underneath, whereas nowadays everything is cut down. Shortly before the war, Messrs. Gordon and Gunton had a building in which they were going to use " Mack " partitions throughout, putting only about $\frac{1}{4}$ in. of plaster on them ; and yet their clients required that all the wiring should be hidden. They had decided to get over the difficulty by putting in copper-sheathed wire buried in the plaster. The building in question was that of the British American Tobacco Co. on the Thames Embankment ; it was wired to our specification with 15 to 20 miles of this wire plastered over, and it has given no trouble subsequently. It was successful because the architects were interested in it ; and they took care that the plasterers did not damage the wire, by bending up the ends before the switches and outlets were fixed. This instance illustrates the fact that one cannot adopt the same methods in every kind of building. I think that if the architect would avail himself to a greater extent of the experience of electrical engineers and engineers generally—whether consulting engineers, contractors, etc.—he would be able to avoid many blemishes in his buildings. Most of us have seen a fine building, with marble walls on the surface of which are large, ugly distribution fuse-boards in conspicuous positions. That could have been avoided if it had been specified that the distribution boards were to be sunk flush with the surface, and with proper moulding round them so as to harmonize with the rest of the decorations. The contractor cannot put in refinements of that kind unless they are specially asked for, and in most cases the work goes to the contractor who sends in the lowest tender. There are many other cases where the architect should co-operate with the engineer. Who has not seen a lift shaft where the lift maker has been absolutely cramped because the architect had not given him a sufficient run below the lowest and above the highest floor to enable the brakes to act properly? In this connection I may say that it is all-important that the co-operation of the engineer and the architect should begin at the earliest possible stage in the design of the building. Generally the architect first completes his plans, and then at the last moment the electrical engineer—be he consulting engineer or contractor—is presented with a set of plans, and asked to make his arrangements comply with them. If the co-operation takes place early it is possible to lay out the building properly, and in modern buildings, such as those now being erected in Regent-street and Oxford-street, one has to build everything round the sprinkler pipes, which apparently must run in a definite position; after the latter have been fixed the electric wires can be laid out. Very often, by some modification of the columns running up the building, one can find a place on which to run up the tubes, and to fix distribution boards, switches, etc. I was very interested in the various suggestions made in Mr. Beauchamp's paper as to the ways in which electricity could be used in buildings, and in which the engineer might be of assistance to the architect. There is one thing omitted from that list, however, which is of some importance, namely, the help which the engineer can give in preventing draughts. About 25 years ago I examined an office in the City in which the draughts were a source of complaint. There was a large skylight over the room, which was very well heated by radiators; hot air was rising, cooling itself against the cold glass, and sinking on to people's heads, as it does in church if one sits near a side window. As a remedy an ordinary piece of resistance wire was wound backwards and forwards under the skylight on some porcelain insulators; and a current through it effectually stopped the draught. A similar problem at the Carlton Club was solved some time later by similar means. Referring to private plants, I would urge on architects who are responsible for country-house installations that they should not economize on batteries too much. It generally leads to trouble, and will do so to an increasing extent in the future, because people are now being educated up to desiring electric radiators. They will want them worked from their private plant, which will not be large enough unless due care has been taken, because with the introduction of improved lamps the capacity of the plant has in many cases been reduced. The possibility of other requirements than lighting should be taken into account when considering the size of such plant. With regard to the use of electricity for heating, I do not think that, except in very special cases, any one of us would recommend electricity at the moment for the complete heating of a building—certainly I would not. Personally, I think the proper way to heat a building is by means of hot-water radiators with, in addition, electric radiators. If the room is entirely heated by hot-water or steam radiators, one of two things happens: either the temperature is merely sufficiently high to keep a person warm if he be so on entering, or else it is so high as to make the room appear oppressively hot after being in it for some time. It reminds me of a room lighted entirely by reflected light; it is not satisfying. Sufficient heat ought to be supplied by means of hot-water radiators to give a reasonable temperature, and at some part of the room, not necessarily the fireplace, an electric radiator should be provided for the benefit of people entering cold. In that way are the maximum comfort and the cheapest system obtainable.

**Mr. A. O. Collard**: One of the difficulties in the past which has affected co-operation between architecture and electrical engineering has been that the latter is a comparatively modern profession and architects have sometimes not been quite clear as to what extent their advisers might be disposed to favour the manufacturing side rather than the expert advisory side. That feeling is fast disappearing, and we know now that we can consult advisory electrical engineers who will be perfectly frank and not be influenced to the least extent by any question of cost or manufacturing motives. You, as electrical engineers, join that happy band of painters, sculptors and other art workers who help us to complete and adorn the buildings we produce. The points which Mr. Dykes has mentioned are familiar to most of us. We have all made mistakes similar to that of not sinking lift shafts deep enough. All these things are due to want of thought. I notice in one of the papers a reference to the desirability of the architectural student learning something of the use of electricity whilst still in his student period. I think that is an excellent idea, and if in the curriculum of our architectural schools one or two lectures could be given each session on your particular subject, by an expert, the students would never regret it. Mr. Masters referred to the absurdity of installing only one plug per house. Unfortunately, we all know houses where the addition of one or two plugs per room would be an immense advantage to the owner. Architects, however, are frequently up against the difficulty—one out of many, of course—of the economy of clients when counting the cost of their houses. It is extremely difficult to persuade a client that he had better have three plugs per room (or, in a large room, perhaps more) even if he does not intend to use them immediately.

**Mr. F. Tremain**: I had been looking forward to these papers with the greatest interest because for some time past I have been wondering what the all-electric house is to be like. I had hoped that the author of the architect's paper would put before us some glorious design for an all-electric house, on the lines of some of those now to be seen at the Architects' Exhibition at Grosvenor House. I confess to being a little disappointed that he has not done so. I was very glad to hear, however, that he appreciates the advantages of electricity for ventilation purposes, and that it would open the way for abolishing chimneys in houses. I have two suggestions to make about the all-electric house. I was attracted last year at a Bristol Exhibition by concrete blocks for building which were very nicely coloured and looked almost like Aberdeen granite; these are made hollow, so that there is a space from the floor to the roof in all the walls. I consulted the exhibitors as to the possibility of providing within these concrete blocks transverse channels for all the necessary wiring and ventilation ducts. There appears to be no difficulty in doing this. The blocks are made, I believe, by a large number of people, and it is claimed for them that they save 30 per cent in labour of erection, 75 per cent in mortar and 25 to 50 per cent in haulage costs. It is claimed, also, that this continuous cavity in the walls and partitions prevents overhearing. It occurred to me that, with these channels provided to all the necessary points, it might be possible to use bare or lightly insulated wire for the main internal wiring, thus reducing insulation troubles. It may be necessary, of course, to use porcelain insulators at certain points, but it would seem to facilitate the permanent wiring of a house in a very substantial manner, giving access to a large number of points for future use. These hollow walls would also provide space for exhaust pipes for ventilation, and I suggest that they could also be utilized for tubes for the vacuum cleaning of the house or block of houses. In the case of a block of houses built together this might be done with one vacuum pump, very much on the lines of the pneumatic despatch tubes employed by the Post Office in London and elsewhere, which have been in use for 50 or 60 years. There would be nothing new about such an arrangement. A small electric motor, with switches at several points, would be sufficient for a block of houses or flats, and the pipe could be led up to each hall, or landing. By running the cleaning tube, which would be quite light, over the walls, floors, etc., all the dust would be removed to a common dustbin. I should like to know whether Mr. Hooper has heard of the concrete blocks to which I have referred, and whether there are any objections to their use. I suggest it might be possible to build 4 houses together, with a central shaft or area 12 ft. to 16 ft. square. There would be a sunken entry to the central area, through which all the wires and pipes for drainage, ventilation, etc., would be taken to the inner corners of the houses, and the two front houses of the group of four would be semi-detached, separated by about 6 ft., so as to admit ladders, etc., to the central area, at the base of which would be a chamber for main fuses, meters and pneumatic plant. As this concrete material can be made in any desired shape, I suggest that there should be bold circular windows so as to give all the four houses an outlook to the front. There should be no difficulty, if desired, in making such houses into 8 flats by adding additional stories, and the whole of the various services for these flats would come in at this one entrance, with a clear run right up to the roof. Within this area the workmen would make all the necessary repairs, and it would light and ventilate lavatories, kitchens, etc. As regards the interior of the all-electric house, I suggest, for Mr. Beauchamp's consideration, that there might be a low mantelpiece in the dining room to form a buffet, and below it something like the interoven arrangement, only of an electric type, with the upper part used for warming plates, etc. This mantelpiece, when not in use for food, could be utilized for the usual ornaments, and one could sit round the fire. As regards the drawing room, I was pleased to hear Mr. Hooper draw attention to the fact that flowers are not injured by electric light. Outside the drawing room there should, I think, be a conservatory, with the blinds on the outside of the conservatory instead of between it and the drawing room, so that the flowers would have a decorative effect by night as well as by day. There are a good many details which I could mention did time permit, but my chief point is to inquire whether these concrete blocks are really effective for building. If so, the channels provided in them appear to be just what is wanted for renewing the air, and taking away dust, as well as providing for economical wiring.

## Adjourned Discussion on the Papers by Mr. Hooper and Mr. Beauchamp, 22 March, 1923.

**Mr. A. E. Munby**: I am entirely in favour of the extension of electricity to all sorts of purposes. Nothing is more flexible; nothing is more mobile. I do not see why, in 10 or 20 years' time, there should not be a very great extension in the use of electricity, particularly for small domestic services of different kinds. The subject is a very technical one, and although we, as architects, have a good many duties in connection with it, I do not think that we can be expected to grasp all the technicalities of the electrical industry. Electrical engineers will probably reply that it is not necessary that we should do so, but we accept certain duties and obligations in connection with electrical work, and these we ought to fulfil. Co-operation with electrical engineers is very necessary in many cases, but the fact remains that the majority of our work hardly justifies the calling-in of a consulting electrician, and therefore I think that you will always have to be prepared to remain suppliers of the material requirements of electricity, and also, to some extent, advisers of the architectural profession. I have a great deal of sympathy with the demand for adequate specifications for fair tendering. As a younger man, I endeavoured to write electrical specifications for sub-contractors, but now I put matters into the hands of one or two firms, whose work and reputation I know, rather than commit myself to a great amount of technical detail. I venture to suggest that what is needed is a draft electrical specification in a lay form to indicate the kind of things which an architect should specify and should decide, in order to enable tenders to be fairly taken. If your Institution should decide to take up anything of that kind, as far as I can I am quite prepared to see that it gets a good hearing from architects and is published in our *Journal*. I have always been very much in favour of a boy at school, who is going to be an architect, learning a great deal more about science than he does at present, for he has little time afterwards. Our students when they start architectural work have a tremendous field to cover. Fifty years ago the erection of a building was a comparatively simple matter, but nowadays it is very often an exceedingly complicated engineering feat. The architect cannot be expected to be *au fait* with all the different branches of modern engineering, but I think that he ought to have a grasp of the principles underlying the engineering problems which he has to face, and I feel that a great deal of knowledge about those principles could be acquired by a boy either at the University or during his last year at school, if he stops on after the age of 17, without detriment to his general education. If members have any suggestions to make on those lines, as I happen to be on the Board of Architectural Education I should be pleased to bring them forward, and to try to bring home their importance. As to dealings with us, it should be remembered that architects can only deal with electricians as a rule through one firm, that is to say, they are not in the position to deal with the electrical contractor, the supply contractor and so on, and therefore I venture to make here a criticism which may not be wholly applicable to your Institution. The large number of different voltages in various districts is a distinct disadvantage, and the standardization of voltages would probably result in a great increase in the use of electricity. I am at present dealing with a small problem, namely the production of satisfactory ventilation in a chemical laboratory. I told my ventilating engineers that the motor would have to be placed at the top of a high, panelled room, and that as surrounding rooms on all sides would be in occupation there must be no noise or vibration, but I was informed that that was quite impossible, because the system was a single-phase 100-period one. Such systems, I think you will agree, ought to be scrapped. It seems to be no use waiting for the big Government electricity scheme, with its 16 huge power stations ; the industry must get ahead itself. If any improvement is to be made, it must be effected by the members of this Institution. Some time ago I approached my local electric supply company and said that I wished to install some electrical appliances in my house for cleaning boots, silver, and so on, and I suggested that I should be allowed to hire the apparatus. I was informed, however, that although I had my house only on a short lease I should have to buy the apparatus. An ordinary householder cannot be expected to spend £50 or £60 on apparatus which he may have to scrap or have materially altered if he goes to another district. I am of the opinion that the supply companies should loan all this apparatus at a very favourable rate. I would even go so far as to say that they should install the power units free of charge. Variations in the facilities for using electricity have been alluded to. If some quite brief précis of these different facilities available in different parts of the country were made, I think it would be very useful to architects. I feel that the thanks of the Royal Institute of British Architects are due to the Institution for having suggested this valuable subject for discussion, and, if we do not take it up quite so warmly as was expected it must be remembered that we are occupied in a very large number of other subjects as well. An architect has to do everything from testing the drains to designing furniture, and electricity and electrical appliances are only one section, and often only a small one, in the very large sphere of his work. I hope, however, that the valuable papers which have been read and the discussion which has taken place will create an atmosphere out of which something good may come.

**Mr. Justus Eck** : What should be clearly brought out at this meeting is that in the edifice the electrical engineer is distinctly subsidiary to the architect. The architect has a most valuable and interesting position in the world ; he is building into permanent structures his ideas, his thoughts and his experience, and they will go down through the ages, we hope, undisturbed. The engineer, on the other hand, should realize that what he does must be subsidiary to the architect's main views. If we can agree on that, then the architects will come to us ; and I hope they will always come to the consulting engineer, however small the building may be. Mr. Munby has demonstrated the difficulty which a layman experiences in drawing up a specification. What we, as electricians, want is to have the opportunity of hearing from the architect himself what his ideas are early, and not when the building is finished. With regard to our great public buildings, electricity is said to take only a small part in them, but, if one goes through them, one will agree that it can be the offensive part, for all sorts of knobs and excrescences have appeared since the building was constructed, e.g. switches, fuse-boards, connectors, etc. Architects also should realize that, although there are many classes of engineers, there is one class of engineer who should be consulted whenever a question of lighting is involved, namely, the illuminating engineer. As an arc lamp enthusiast, I should like to suggest to the eminent architects who have large houses and hospitals to design that they should put in an arc-lamp bath, because it has wonderful curative properties. We want to know how we can co-operate with the architects, and I would suggest that we should have Informal Meetings with the Architects' Associations and with individual architects and discuss one by one all the headings of the present papers. The question is too large for us to discuss thoroughly in two meetings. With regard to the lighting of museums, the Natural History Museum at South Kensington is lit with 700 inverted arc lamps, which render all the specimens with a true colour effect and there is no reason why that museum should not be open every night in the week. Every public picture gallery or museum could be opened one or two nights in the week, thus enabling many people busy during the day to see the wonderful collections which we as a nation possess.

**Captain R. J. Wallis-Jones** : The need for co-operation between the electrical engineer and the architect is very great. Mr. Hooper summarizes in his paper the uses to which the architect can put electric devices for lighting, heating, ventilation, power, etc., but he does not allude in any way to one of the greatest difficulties in that respect, namely the frequent want of electrical technical knowledge on the part of the architect to employ these devices in the most satisfactory manner. This Institution publishes a valuable set of Wiring Rules, but the real difficulty from an architect's point of view is that it requires a considerable amount of technical knowledge of electrical matters to be able to apply the rules properly and get an installation on sound and satisfactory lines, and architects as a rule have not that knowledge. I am strengthened in saying this by my experience in connection with a very large number of installations in one of the recently developed suburbs. I was surprised to find the class of work that was being done under the supervision of architects; I really think they do not recognize or realize the risks that, in many cases, they are running. I was interested in Mr. Munby's remarks in regard to the motor for ventilation purposes, because I once came across an instance of the want of technical knowledge on the part of an architect who installed some large ventilating fans in a building. When the fans were put into operation, the noise from the d.c. motors was so great that the tenants in the various blocks began to take proceedings for nuisance. I was called in professionally to advise my clients, and I found that by substituting a d.c. motor of a suitable type the noise entirely disappeared. Again, I do not think it is sufficiently realized that periodical testing of an installation is absolutely necessary. The insulation, whatever it may be, is a wasting asset, and the life of the insulation of any conductor varies a great deal, according to the conditions under which it is working. In some cases, for instance, moisture is the trouble; in others, heat. Mr. Beauchamp's paper lays stress on the need for co-operation between the architect and the electrical engineer. The latter is, or should be, in touch with possible future developments and electrical needs to a greater extent than the former. It is sometimes difficult to get the architect to take a long view in regard to electrical requirements. In a case recently where a large building was being erected, I begged the architect to look ahead and make provision, by running conduits and cables to the various floors, for possible electric heating requirements, but I was assured that electric heating was not needed in any way in the building. The building had hardly been finished before the various tenants to whom the floors had been sub-let demanded electric heating. That all meant extra cost and annoyance. The architect is, to put the matter quite frankly, in a very difficult position. If he goes to contractors (I am speaking, of course, on general lines) without a well worked-out and well thought-out specification, he is bound to get tenders which will vary greatly in regard to prices, quality and type of the work and, as it is almost a general practice to accept the lowest tender, the best work is impossible under these conditions. I think that architects generally, if they have any important work to carry out, are well advised to go to a consulting electrical engineer. First, they will thus be enabled to get their tenders all on a common basis, and, secondly, they will get sound technical advice and a minimum of extras. I am of opinion that they and their clients will find that the fees of the consulting engineer are thus very well repaid.

**Mr. A. F. Harmer:** There is one detail of Mr. Hooper's paper on which the whole fabric of electric heating depends. On page 727, under the heading "Heating and Cooking," he says: "The architect and the engineer should never lose sight of the fact that neither of these provides automatically for the essential change of air. . . ." Has any architect designed a domestic building that is really pleasant to live in that is not heated by a coal fire? I have yet to find one myself. The big offices which have been built in this neighbourhood recently are really most oppressive in their heating. I should be glad if the authors in their replies would state if there is a simple yet efficient substitute for the coal fire as a means of ventilation, in buildings as designed. In conclusion, I think that wiring rules are necessary, but they want carrying out in a very broad-minded way.

**Mr. F. C. Raphael:** I should like, in the first place, to endorse what Capt. Wallis-Jones has said in regard to perished insulation on wires, and to say (particularly for the benefit of Mr. Munby) that I have had similar cases. It is well known to those of us who are electrical engineers that rubber does not possess an indefinite life. I had one instance very similar to that described by Capt. Wallis-Jones, in which there was a small outbreak of fire. We suspected that there had been a water leak at some time or other, but the immediate cause of the trouble was the execution of some building and redecorating. When rubber wires are in the condition described by Capt. Wallis-Jones they give a very good insulation resistance until they are moved, but then the resistance falls to nothing. The architect or builder who had been employed was also given the work of moving the positions of some of the electric lighting points, but had not thought it necessary to obtain the advice of an electrical engineer. He joined the new wiring to the old where he thought it should be done—and the result was a fire. I prophesy that, if this debate is published in the R.I.B.A. *Journal*, 33⅓ per cent of the architects who read it will say: "I did not realize that the electrical engineer was *that* sort of man; I thought he was a kind of foreman whom the builder employs for doing the electrical work." Another 33⅓ per cent will say: "I did not realize that the electrical engineer was *that* sort of man; I thought he was the fellow who sends travellers along to us to bother us to specify their lamps, cables and things." The views of the remaining 33⅓ per cent have presumably been expressed by the architects who have spoken in these joint discussions, and I sincerely trust that we shall have been successful in making them understand that there is such a thing as an electrical engineering profession. The electrical engineer's work is really as much a matter of designing as the architect's work in planning the building, although it is, of course, an entirely different class of design. If we were to attempt to teach them our job, I am afraid that they would not have time to learn it even if we had the time to devote to the necessary instruction. In the case of a big public building, there is bound to be trouble or wastage if the architect carries on without the advice of a competent electrical engineer. He can, of course, give a free hand to the best contractors, but I think that his client would have just cause for dissatisfaction if he did. A short time ago I got out the plans for the electrical work for a very large building, and I made a provisional estimate for the report of the architect to his client. This architect realized that it was necessary to get into touch with the electrical engineer at the time he was getting out his plans. To the best of my recollection, the cost of the whole of the electrical work, including lifts, in that building was less than 5 per cent of the whole cost of the building. The electrical engineer's fee is only a percentage of this percentage, and I fear that architects have not considered the question thoroughly when they refer to the extra expense to their clients. I affirm that in a very large number of new ferro-concrete buildings the consulting engineer's fee is actually saved by the saving in cutting away and making good. I recently had a large ferro-concrete building to deal with, in which, as is usual in such constructions, it was a matter of considerable difficulty to find room for the pipes carrying the wires. In this case the architect had not forgotten that such pipes have to go in the buildings, the position of the electric lighting points was decided upon at the outset, and we were able to fix the exact position of every pipe run. The work has already started and I do not think that there will be much more than £100 worth of cutting away in a building costing many hundred times that sum. Brass pipes were mentioned by Mr. Dykes; it is only in very special cases that this expensive luxury is required. I have put thousands of feet of ordinary conduit in buildings and have never yet had any condensation trouble. Another instance in which the client might have been saved a considerable outlay occurred in connection with the rebuilding of the vaults of a fairly important bank. After the work had been completed, without the assistance of a consulting electrical engineer, the Fire Office inspector objected to the conduits being brought through the ceiling of the vaults. The alterations that were necessary to conform with his requirements cost between £30 and £40, exclusive of supplementary cutting away and making good, and my fee. If it had been done in the proper way at first, the cost would have been less than the method adopted originally. The question of lifts has also been referred to by Mr. Dykes. The architect can, of course, put the whole thing entirely into the hands of a reputable maker, but if he wants competitive tenders he would be very unwise if he did not see that a thoroughly technical specification was drawn up and a man who understood the electric side of the work called in to adjudicate on the tenders. Glare has been mentioned a great deal, but no electrical engineer who has had a fair experience in lighting buildings should be unable to prevent it. The room in which we are assembled at present should show that we are capable of going to the opposite extreme. Mr. Hooper believes that many buildings are disfigured by façade lighting, but, on the other hand, exhibition buildings, and others of that sort, have always been designed to be lighted in that way. As a general rule, however, I agree that this type of lighting is wrong from an æsthetic point of view. Museum lighting has been referred to. There is no great difficulty in it, but, unfortunately, in London the museums are usually under the control of the Office of Works, and in the provinces they are usually managed by the local authorities, so that the independent consultant does not get much experience in regard to them. I can only instance one case in my practice: a museum of a medical school, 90 ft. by 75 ft., and 45 ft. high. I simply put in ordinary good semi-direct lighting for the main lighting, and hidden reflected lighting for the shelves and showcases. There were two galleries, and on the floor level there were shelves under one of the galleries, so that rather peculiar lighting was needed. We found, however, that the system adopted worked perfectly well, and had the additional advantage that the students could switch the lights on and off as they wanted to inspect the various samples. I should like to suggest that Mr. Beauchamp's paper lays too much stress on the argument of cheapness. It is well known that for some applications electricity is cheaper, while for others gas is cheaper. In our advice to the architects and their clients we should be a little more impartial and simply put the facts before them, instead of giving the impression that we are purely salesmen. Salesmanship is all right when it is a question of direct dealing between the seller of an article and the purchaser, but in the design of a big building salesmanship is out of place. Mr. Hooper's note on chimneys has already been mentioned, but there is a further point to which I should like to refer. The summer months are the hottest months in the year, and are the months during which ventilation is most needed, but that is just the time when the ordinary householder closes the register at the bottom of the chimney. I maintain that the chimney was never designed as a ventilator, but as a draught producer. It can only be a sort of excuse for not using electric heating that it has suddenly been discovered that the chief function of the chimney is to ventilate a room—in spite of the fact that it is provided with a register, the express purpose of which is to close the chimney during the hottest months of the year when ventilation is most essential.

**Mr. H. Shepherd:** The last speaker referred to façade lighting. From my point of view, at any rate, a great deal of the street lighting nowadays is very objectionable. The large number of ill-designed colour schemes one sees spread over the façades of buildings have not, I am certain, been designed by architects. The desirability of consultation between the architect and the electrical engineer, or real co-operation between them, is, I think, obvious, and I am in perfect accord with it. Architects who have to deal with a large building scheme would be well advised to take into consultation an electrical engineer, not during building, but when preparing the plans. For my part, I have invariably sought the advice of a consultant when I have had a large scheme in hand, and I have done so from its inception, when it was still on paper. Nowadays the many ramifications and requirements of which an architect is expected to have a general knowledge may lead to trouble later if one does not make proper provision not only for the general lighting and power, but for telephones, bells, etc., and ducts for the heating and ventilation of the air in the rooms, and for the periodical extraction of dust therefrom. It must be remembered, however, that architects are in the same position as engineers, and no doubt your clients also expect of you a great deal more than they are entitled to demand. I endorse and certainly agree with what Mr. Munby has said in regard to voltage. It is a question which is perpetually cropping up, and is a source of very great trouble. Sometimes when I have asked for advice from electrical and other consulting engineers I have been told: "Show us the building, and then we will tell you what to do." It might be of great mutual advantage if a joint committee were set up to consider and advise on certain points which need elucidation. For example, I should like to ask you, as electrical engineers, what is the best floor for a battery room? What is the effect of dilute acids on cables and wiring? From your point of view, would you prefer a concrete floor with a hard finish or a tile floor in, say, a generating station? I should also like to ask what would be about the average lives of first-class wiring installations of, say, "Grade" and "Class" kinds? We do not know whether in, say, 15 or 20 years' time a great deal of the wiring will have to be renewed, but you electrical engineers can tell us. Such information and the settlement of questions of this kind is, I suggest, where your experience would be invaluable to us, as architects in the preliminary design of a large building scheme. Capt. Wallis-Jones mentioned periodical testing. I have found when acting for companies that one can get a Board to agree much more easily to regular inspection, testing and maintenance than a private client, because they more quickly realize the business advantages. We have, however, the same difficulty with individual clients as you have, and although we try to persuade them to have proper periodical tests carried out, after all it is the man who pays who calls the tune, and one may give him advice, but he does not always take it—I daresay you have had that experience. There are many cases in which I suggest it would be very useful to have a joint committee. If such a committee were set up, I believe that the Royal Institute of British Architects would welcome the opportunity to consult with you on any points in regard to which we could be of mutual assistance.

**Mr. H. Cubitt:** It has been said that we should confine our remarks to the question of co-operation between the two professions. One point occurred to me, in reading through Mr. Beauchamp's paper, in regard to which the electrical engineer might be of very great assistance to the architect. It is with reference to electrical cooking. Nearly all architects, I think, would like, if they could, to put electrical cooking into all their new buildings, but they hardly ever do it because of the cost. Obviously it is the best form of cooking that we can use, but, on account of its cost, we are generally compelled to employ gas. The ordinary coal-burning kitchen range has, in my opinion, become a thing of the past, and we only put it into a house if the client particularly requires it. In an ordinary modern building it is our practice to put in an independent boiler for hot water and heating—perhaps two boilers or perhaps a combination—and a gas stove for cooking. If, instead of gas, we could use electricity, I am sure we should get very much better results, but the cost is too high. On page 733 Mr. Beauchamp says: "The combination of electricity and other methods of heating is of interest. . . . Ovens or other cookery equipment have been made for partial heating by the flue gases of anthracite or coke furnaces, the final cooking temperature being provided for by a limited use of electric elements." I suggest that development along these lines may make electric cooking much more general. If something could be done whereby we could employ part of the heat from the hot-water boiler in raising the electric stove to a certain temperature permanently all through the day, with the actual cooking temperature added to it as required by means of electricity, it would give us an opportunity of doing what we all wish to do, namely, make a general practice of using electricity for cooking. Perhaps it may be said that these things are very nice in theory, but that the actual developing of them and putting them into practice is very difficult. On the other hand, possibly it is our business as architects to say what things we should like, and in electrical matters yours to try to produce them.

**Mr. H. J. Cash:** Mr. Beauchamp on page 735 suggests the possibility of setting up a joint committee of the two professions, and this idea has been taken up by one or two speakers. Mr. Beauchamp suggests that one of the objects of the committee might be to set up some method of instructing architectural students in electrical matters; but I think that such a committee would also do useful work if it instructed illuminating engineers in architectural matters. I cannot help feeling, as an electrical engineer who has very little knowledge of architecture, that the illuminating engineer in most cases simply sets out to provide illumination, and, if he gets the required amount of illumination into a room, he thinks he has done a good job of work; but probably the architect will say: "You have reversed every shadow I had provided for; all your light is coming from the wrong direction." A committee such as has been suggested might possibly keep us from making mistakes of that description. As a contractor, I should like to support those consulting engineers who have said that they think architects should, whenever possible, employ them. I am always willing to submit schemes and tenders without a consultant intervening, but I feel sure that all contractors would prefer that consultants should be called in. I know that consultants are always called in on large jobs, but even with small ones I cannot help thinking that the consultant's fee would be saved by the economy thus secured. In the old days we were only concerned with lights, and the architect knew how many lights he wanted and where he wanted them; but to-day there are power circuits to be considered, and I may be asked to provide 10 such circuits. First of all I have to find out what they are for—irons, radiators, or what not. If I am told they are for radiators, I know very well that my competitors will tender for 1 kW radiators, but I may know that they ought to be 2 kW or 3 kW. What am I to tender for? That is the case of a small job, but there are also the intermediate ones, such as country houses. I had a case the other day where the architect knew his contractors, and only went to two or three from whom he knew he would get good work. I heard afterwards that my price was the lowest but was not accepted because the contractor whose tender was accepted had put in a larger battery than I had; he had put in a 200 ampere-hour storage battery, and I a 120. I discovered later that he was tendering on 50 volts and I on 100. My battery was really larger than his, but it appeared to the architect to be smaller. After having suffered in one or two cases of that description, I decided that I must protect myself by quoting in every kind of way I could think of. The result was that the architect had no idea which of 15 alternative combinations was the actual tender. All this kind of thing means higher overhead charges to the contractor which the client has to pay in the long run instead of the consultant's fee. Mr. Beauchamp and several other speakers have referred to heating, and mention has been made of the use of low-temperature hot-water systems with electric radiators. Mr. Beauchamp has given some of the advantages of that method, but one or two he has omitted. The great disadvantage of hot-water heating is that one sets out to warm a room by overheating the air. Of course, for centuries past we have made warming the room our objective, but that seems to me to be wrong; we should not aim at warming the room so much as at the comfort of the people occupying it. On a cold winter's day one is quite satisfied to sit in a warm, sunny corner of a room, although the room itself is at a lower temperature than one would otherwise be ready to tolerate; it is the radiant heat of the sun which makes it comfortable. That fact should be taken into consideration a great deal more in the future than it has been in the past. With hot water and steam heating the temperature of the heating units must always be very much higher than the required temperature of the room, resulting in overheating of the air and discomfort. With a much lower general temperature of the hot-water pipes, not only is fuel saved (for it is much more economical to keep up a room temperature of 50° F. than 70° F.) but the air is not overheated, and the objection to hot-water radiators almost entirely disappears. If the hot water is kept at a sufficiently low temperature and the electric radiator is simply switched on when needed, then, provided one is sitting within range of the radiant heat, it will, I think, be found that the resultant temperature of the room need not be anything like so high as has been necessary in the past in order to make it comfortable. I suppose that the majority of those who have become accustomed to a coal fire will want to keep their own particular coal fire, but I cannot help thinking that, even if our sons are of the same opinion (which is doubtful) our grandsons will say: "We will not have them; they are nothing but smoke producers and work makers." I am convinced that electric radiant heat, probably in conjunction with low-temperature central heating, is the method of the future. Mr. Beauchamp says with reference to church lighting: "Latterly there has been a tendency to introduce some little dramatic element into this work," and goes on to quote some notes with which I supplied him. It is only a matter of the exact meaning to be attached to the word "dramatic." I do not agree there is anything dramatic about it. A great point with regard to that system of lighting of churches is that, since the architectural design of the interior is so important a feature, the cost of electric light fittings in the ordinary installation must, in order to harmonize with the building, in most cases amount to more than the cost of the installation, whereas the scheme of church lighting quoted by Mr. Beauchamp reduces the cost of the fittings to next to nothing. I have been told that such a scheme, although it apparently provides for the satisfactory lighting of the congregation, must suffer from the fact that it puts all the glare into the eyes of the clergy. That point has not been raised in the present discussion, but it might be of interest to state that in no case have clergymen had anything to complain about; in fact, generally they are very pleased. One of the obvious advantages of electric lighting is that the lights can be turned down when the clergyman is in the pulpit, and when occupying the clergy desk he does not have to face glaring lights.

**Mr. E. C. Barton** (*communicated*): As the greatest single worry of the housekeeper is dust, this occasion should not be lost of drawing the attention of architects to air filtration as practised in power stations, in order to convince them of the possibilities of filtered air in public buildings, clubs and hotels. Vacuum cleaners are invaluable in the struggle against dust after walls, floors, carpets, furniture and books have become painted with it, but they only mitigate the evil. For private houses they will probably survive, but not in buildings of more than half a million cubic feet capacity. A club or hotel of such dimensions would, according to the figures given in the *Builder* (28th October, 1921), require only one complete renewal of its air content per hour, or 4 500 cubic feet per minute, an insignificant performance compared with the ventilating of a 10 000 kW generator. Incidentally, the hotel could guarantee almost any climate to its patrons by using refrigerated water in a spray filter to dry or cool the air. In libraries, where the battle with dust never ceases and where the books all succumb eventually to the enemy, air filtration should prove indispensable.

**Mr. W. E. V. Crompton** (*communicated*): I should like to make a few remarks dealing more definitely perhaps with a few of the everyday points that occur with reference to the actual co-operation of the architect and the electrical engineer. Although the necessity for this co-operation is a truism, often in practice it is found to be superficial and belated. Co-operation is essential from the commencement and involves the explanation by the architect to the engineer of the architectural idea upon which the design is based, so that the engineer becomes infected—as it were—by the imaginative idea in the architect's mind. He is then in a position to play up to it. In other words, it is necessary for the architect to make clear to the electrician the kind of finishing he contemplates for his wall surfaces, be it plaster, hardwood, marble or what not; whether the metal to be used be silver, bronze or iron; the use to which all rooms are to be put and even certain peculiarities of his client as far as he—the architect—has been able to find them out; not only all this but, which is quite as important, it is essential for the engineer to appreciate the kind of effect or appearance at which the architect is aiming in each room or place. Seeing that increasing provision has to be made for pipes and wires in all buildings, it is advisable for the architect to design so that additions can be made easily and thus do his part in playing up to the engineer, so as to avoid the haphazard way in which subsequent wires and tubes usually have to be run. There is no end to development: for instance, it will not be long before external radio wires will be obsolete, and provision will then have to be made inside the house for them. It is thus a question whether all skirtings and dado mouldings, etc., had better not be fixed with screws so as to be easily movable, and whether all corridors, not only in public buildings but even in the smaller domestic buildings, should not have counter ceilings so as to provide runs for future wires and pipes. So much for the architect: let us now consider the engineer. It is for him to grasp the design so as to ensure, for instance, that the position of switches always tallies with the centre of the style of the panelling behind which it is fixed. He must also appreciate which are the axial lines of the design and which are the correct architectural centres of the various spaces so that various fittings may be fixed in the right position, for the busy architect cannot be expected to mark with chalk the exact position of every electric light point. He must also realize that the proper size of wall plug—that is, as far as appearance goes—for a skirting 1 in. thick is not necessarily the size to use when the skirting is 1½ in. thick. Something might be done to make the arrangement of main switchboards and cut-outs more presentable: the present arrangements seem to be on a par with the untidy dashboards of motor cars 10 years ago. These dashboards are now mostly designed and not haphazard: a similar element of design is required in the switchboards, etc., of the ordinary electrical installations. Mr. Hooper rightly alludes to the irritating and injurious nature of the excessive candle-power often used: this glare can be done away with by proper shading, and yet the manufacturers of shades do not seem to be as helpful as they might. The other day I was looking for some electric fittings in one of the largest showrooms in London and could not find a glass bowl that subdued properly the cold white light of the modern gasfilled lamp. There was not in the showroom, or apparently available, a shade warm enough to counteract this whiteness, which is so trying to most complexions. This question of co-operation between the architect and engineer is only a part of the larger question of the general duty of the architect as co-ordinator in chief, which, owing to the complexity of our civilization, becomes more and more an important part of the architect's activity as time goes on. Perhaps my bias as an architect makes me say that this is as it should be, but I think it is based upon the well-founded assumption that the architect's work, having its basis in the humanities, must have a large outlook and take precedence over engineering activities which are based upon utility.

**Mr. W. A. Gillott** (*communicated*): It is by discussing various problems that the best of ideas are evolved; therefore a co-operative meeting between architects and electrical engineers, such as this, is sure to do much good and perhaps clear away any misunderstanding that may have been present in the minds of a few of us. I propose to make a few remarks upon the question of fire risk. Unfortunately, when the origin of a fire is unknown it is often attributed to electricity, but, as electrical engineers know, this is invariably not the case. If one employs a good firm to carry out the electrical installation there is very little risk of fire due to the so-called "fusing," and I suggest that cigarette smokers are responsible for considerably more fires than is electricity. It is agreed that a very small number of fires may be caused by electricity, but upon investigation it is usually found the installation was either a temporary one or that the work was done by incompetent people. I therefore suggest that all architects arrange for their electrical work to be performed by first-class electrical contractors; it costs no more, and relieves them of any anxiety. The use of electricity for cooking and heating is spreading very quickly, and architects will be well advised to consult electrical engineers upon these matters when new buildings or houses are to be erected, as quite considerable sums can be saved in the construction of the building by eliminating certain chimneys—often unused if erected—and by allowing for ventilation in a different manner. In dealing with kitchens for hotels, restaurants, cafés, etc., I should like to see the architect call in the electrical engineer before his plans are complete so as to ensure sufficient working space and economical lay-out of the cooking appliances in the kitchen. These are often left to the last, and any odd corner is utilized for the cooking of food. The kitchen is the heart of the whole business —if food and service are not properly provided, the concern will be a failure—therefore I contend that it is essential that the kitchen be given more consideration than it often receives. A well-planned approach for goods to the same, and quick and easy dispatch to the dining room, etc., is the key to success. I am speaking with experience when I say that the investment of a little money upon kitchen design will return many times the amount spent. Mr. Beauchamp draws attention to the question of tariffs. It is desirable that architects consider the comparison of costs of other fuel before making a definite decision: what may appear dear in one district is no doubt cheap in another. There are so many other advantages to be considered that it is not until these have been carefully studied that a true decision can be arrived at. It is too much to expect architects to employ fully qualified electrical engineers upon their staffs, but I am of the opinion they would do well to consider the question of retaining, at a moderate cost, a consulting electrical engineer whom they could call upon at any time for advice upon matters that arise and who could keep them up to date in new ideas and inventions likely to be of benefit to them. I am confident that the formation of the committee suggested by Mr. Beauchamp would be of immense service to both professions. It is, of course, understood that the committee would not displace the consulting engineer, but would merely assist the exchange of views and progress regarding electrical matters. I sincerely hope that his suggestion will be taken up and become an established fact.

**Mr. J. Johnson** (*communicated*) : A telephone installation is now recognized as a necessity for all business premises, and yet it would appear that this matter is sometimes overlooked by architects when provision is being made for the various services in connection with a new building. I should like to point out that the telephonic cabling of a building often involves the provision of a number of large cables with risers from floor to floor, and suitable distribution points have to be selected. In my opinion the provision of a telephone service should receive as much attention as any other service. Telephone engineers are constantly on the look-out to note preparations for constructing large buildings and to ascertain the use to which the buildings will be put, but often the design of a building is settled before the engineer is aware that a building is about to be erected. Co-operation between the architect and the electrical engineer would overcome this difficulty if it were discussed whilst the building was in course of design. Telephones are generally required in the first occupation of a building and are not usually considered until the building is ready for occupation. A more satisfactory lay-out would be obtainable, a good deal of surface wiring avoided, and delay in providing the telephone service reduced to a minimum.

**Mr. G. W. Keats** (*communicated*) : My experience has proved to me conclusively that the principal factors are the question of finance and the education of the user. In regard to the former, the London County Council were willing to grant loans for the equipment of premises up to a period of 10 years. I understand that the Electricity Commissioners are not quite so liberal in this respect, so that the development of electricity for domestic purposes is hampered at the commencement by the fact that the gas companies can install their gas stoves and maintain them out of revenue, as in the case of the electricity undertakers, and all they have to do is to give their shareholders a reasonable dividend : whether the dividend is made out of supply of gas to the particular stoves, or from residuals, or other sources, does not matter. Electricity undertakings, however, who have not a substantial reserve fund, are compelled to apply for loan sanction, and, so far as I know at present, the maximum period that has ever been allowed for such loan sanction is 10 years. The value of the type of stove which is usually installed in bedrooms of the cottage type of house is well known ; the cast iron is usually the cheapest possible. A loan of 60 years is granted for this. I think it is beyond criticism that the up-to-date electric cooking stove or radiator (and we must bear in mind that most undertakings are prepared more or less to maintain them out of revenue) are infinitely of better construction, and yet we are limited up to the present to a loan repayment period of 10 years, whilst for paint, distemper and glass a period of 60 years is allowed. The Electricity Commissioners have assisted the development of electricity more than they possibly realized at the time, by extending the loan repayment period for services from 12 years to 25 years, but we are still faced with the short-period repayment for meters, house wiring and cooking apparatus, viz. 10 years. It would be interesting to know what would be the price of gas if all the apparatus which the gas company supply were capitalized under conditions similar to those which hamper the electricity industry. Gas undertakings, by reason of the income from residuals, are able to make ends meet, but electricity undertakings, who have no such income to rely upon and who do not overcharge their flat-rate consumers for the benefit of prepayment consumers, are in an entirely different position. These remarks may appear to have little connection with the title of the papers, but I suggest that, whether there is co-operation or not, finance governs the whole. When the Eltham Housing Estate was commenced at Woolwich, it was admitted at the time, when the cost of construction was high, that there would have been a saving on each house of at least £25 if the chimney breasts and stoves in certain rooms had been omitted : probably to-day that saving might be reduced to something like £12. This saving would naturally go a long way towards the cost of installing electricity in the house. That there should be co-operation between architects and engineers must be obvious to everyone. Before there was a single house constructed at Eltham I suggested that the ideal house would be one which as far as possible consumed its own refuse by means of a slow-combustion stove which would provide all the hot water required in the house, whilst limiting to the minimum the amount of incombustible house refuse to be removed ; and that there should be heating plugs in all the rooms, because with the particular type under construction it would only be in the case of illness that heating would be required in the bedrooms, and this could be temporarily met by the free loan of radiators. In all the houses which have been given a full equipment of electrical apparatus there has been practically no complaint, with the exception that, through not having slow-combustion stoves, water has to be boiled by electricity, which I have found from experience to be somewhat slow. I am certain that with proper co-operation between the architect and the engineer, practically the whole cost of electrical equipment could be covered by the saving in the cost of construction, quite apart from the well-known savings in the maintenance of the property.

**Mr. Francis Hooper** (*in reply*) : I should weary you were I to attempt to deal with all the interesting comments that have been made during the discussion, but I should like to thank you for dealing so indulgently with me in this attempt to show some of the common interests of one body of men with another. I do not minimize the responsibilities nor the opportunities of architects and electrical engineers as affecting the welfare, or the reverse, of their fellow-men.

You have already invited doctors to put before you their points of view, and they too have assured you that they value the work of the electrical engineer.

We are not in a new world—a fact which some critics seem to forget—but circumstances change, and conditions change. We architects desire your aid, not only in factories but in every undertaking. Our activities are fundamentally social, and vitally concern the health and well-being of the community at large. Architects look to engineers to assist in overcoming or mitigating the serious injury and loss caused by the smoke and impurities of our towns. Users of underground railways should daily thank you engineers for what you have done there; and we look forward to equal wonders in the future. For the driving of machinery, and the many improvements in the workshop, architects recognize electrical power as important aids alike to builders and the allied industries under their direction.

The initial point for consideration appears, from the discussion, to be the best method of distributing electric energy in the many varied types of buildings both new and old for easy use, readily accessible for repair, extension or alteration, with the least disturbance of floors, walls and ceilings. Specially constructed channels for mains may often be desirable and, as has been suggested, for distribution exposed wiring carefully studied as regards both safety and sightliness would offer important facilities. Skirtings, cornices, frieze-rails and ceiling-ribs might be turned to account in some cases for this purpose, without detriment to decorative or other amenities.

Allusion has been rightly made to the consulting engineer, and the payment for brain work. I cannot speak for the Royal Institute of British Architects in this matter, but only as an individual. I am, however, convinced that the work of both architect and engineer is better understood now than it was. Many employers now recognize the value of both in all their undertakings, and, that being the case, clients, whether companies, corporations or private individuals, are more ready to take and pay for their advice in regard to questions of sanitation and organization than was the case in the past. I am sanguine that this meeting may assist our members to recognize the valuable assistance that we may get by consulting electrical engineers as independent advisers. We may say: "You are only concerned in giving advice to secure the best results."

I do not know that it falls within the province of architects to draw up electrical specifications. I think most architects are satisfied to say: "We want certain things done; what do you advise?"

Reference has been made to the fire risks of electric lighting. I am confident that electrical engineers will hold that these are almost negligible.

Some of our museums have been lighted electrically, but this is not the case with the National Gallery, nor, I think, with the Portrait Gallery adjoining. The lighting of our museums and public picture galleries for use during winter evenings I regard as an important social matter: so large a portion of our working community now loses the value of our museums, which are closed at 5 or 6 o'clock. Your President assures me that if allusion is made to this question during the course of this discussion it may be considered by your Council, who will take what steps they see fit to bring their views to the knowledge of those in authority. The matter of guardianship is a formidable objection to any concession, but it might be possible, at intervals, to close by day and open, for half the usual number of hours, at night. This would give the illuminating engineer his chance, and we should look to him for great advances in concentrating the light. Go to the National Gallery and look at the "Raphael," for which a huge sum has been paid. Imagine it lighted from the point intended by the painter in a way well within the power of the electrical engineer, and all will then recognize its true value. Our sculpture, too, loses interest, in many cases, from the same cause. By concentrated lighting that could, to a large extent, be avoided. We should get a scheme of illumination and of education which would extend from public to private galleries, and so make all far more interesting than at present.

I ask pardon for having only suggested certain questions which I believe might advantageously be discussed by architects and by electrical engineers amongst themselves, and which might add very greatly to the popularity and efficiency of the work upon which we are severally engaged, and I heartily thank all those who have taken part in the discussion for their valuable contributions, which have added so much to the use and interest of this joint meeting.

**Mr. J. W. Beauchamp** (*in reply*): I am glad to find that in the course of the discussion members and visitors have to some extent answered one another. There are, however, a few points of particular interest with which I should like to deal.

Every speaker was, I think, unanimous as to the necessity for the electrical engineer and the architect to get into touch with one another at an early stage of the work. It is true that one of the architects turned the tables on us rather neatly by instancing the case of an electrical engineer who said he could not think about the lighting of a building until he went inside and saw what it looked like. However, in a general way it is obvious that the engineer and the architect should meet first at the drawing board and not in the building.

The request made for model specifications is rather a difficult one to deal with: conditions change rapidly, but there is already a good deal of information of this kind in existing textbooks and reference books, and I have seen some of it in architects' year-books and similar publications. Within limits it is useful. I dare say the architect is a little nervous of employing it, owing to rapid changes and because he knows that similar matter referring to civil engineering work has to be used with a good deal of discretion. In a general way it is no doubt safer to call upon responsible consulting engineers or contractors.

Several of the architects who took part in the discussion have complained of the difficulty arising from the lack of uniformity in supply pressure. I am afraid the lack of uniformity in prices charged for electricity in different parts of the country is an even greater difficulty, and I am accustomed to hearing these complaints from non-electrical individuals and from the

Press. It can hardly be necessary for me to point out that the electrical industry has more to gain than anyone else from unifying supply pressures: that is one of the biggest undertakings one could possibly call for, and, although the reorganization now going on under the Electricity Commissioners is working towards this desirable end, there is little doubt that we shall have to operate with mixed voltages and periodicities for a very long time to come. It is difficult to blame anyone for this position. In this country we have, electrically speaking, to a large extent to pay for our history. The public service of electricity may be said to have been born here, and, in the early days when conditions were very unstable, pioneers were even proud to set up undertakings with characteristics of supply different from those of their neighbours; the great growth of the business was not foreseen and the possibility of linking up undertakings into a common national electrical network was only dreamed of by a very few.

Mr. Munby complained about difficulty in hiring apparatus. This is a question of commercial development now being dealt with much more rapidly than in the past. In many areas apparatus can be hired or hire-purchased, and this movement will undoubtedly spread. One must never forget, however, that everything that is done must be paid for ultimately by the consumer in some way or other. Apparatus which does not use a great deal of electricity in the course of a year is more difficult to hire out on a close basis than appliances the use of which results in a considerable increase in consumption. In certain lines of electrical work there is every reason for assisting the consumer to obtain appliances, because the result tends greatly to increase the use of electricity, costs fall all round, and low hiring rates are justified. There are other appliances, however, which, whilst bringing to the user an immense convenience and frequently incidental savings far outweighing the cost of electricity, do by themselves consume so small an amount of energy that it is unreasonable to expect the appliances to be hired out on anything but a strictly commercial basis. In some of the districts now pushing domestic electrification it is possible to hire, in addition to cookers, fires and other appliances, the necessary wiring required for their use.

Mr. Eck referred to the objectionable appearance of many of our fittings. There is much truth in this; one frequently sees electrical accessories, switches, fuse-boards, etc., which are quite out of keeping with their surroundings and, through lack of unity in design, take up far more room than they should. This is to no small degree due to the fact that on so many jobs the architect and the electrical engineer never meet.

Reference has been made by one speaker to the necessity of regular inspection and fire risk. The inspection of installations can be overdone; it should at least be related to the size of the buildings and the responsibility on the installations. In many large undertakings there is no doubt a very good case for regular inspection, but one must not place too complete a reliance on insulation tests and purely technical examinations of that kind. By themselves they are insufficient, as one may measure a very high insulation resistance on a network which contains perhaps some very doubtful places. Visual inspection by experienced men goes a long way and is bound up with the methods of wiring employed. Some methods give much more facility for inspection than others and enable faults to be cleared and remedied without undue expense or disturbance.

The ventilation of electrically heated rooms is a question often referred to: it is not difficult, and to argue that electric heating is at a disadvantage compared with the gas or coal fire, which is obliged to have a flue, is not really the way to deal with the subject. The architect and the engineer together can certainly find the means of ventilating rooms without the crude and draught-producing devices with which we are all so familiar.

In connection with electric heating I would here emphasize that in most districts we are only asking for that share of the heating which may be described as "occasional" or "short hour," and if that is given to us it becomes possible to effect very substantial saving on new buildings by cutting out some fireplaces and chimneys, at the same time releasing to the tenant more space, leaving him free to arrange his room without the control which arises from a fixed fireplace, and also saving him the expense of fireplace furnishings.

Mr. Raphael mentioned the very small percentage on total cost of the building which went to the electrical contractor; this is very noticeable compared with the amount that plumbers and decorators receive. There are several reasons for this. In some districts electricity is at present too dear for uses other than lighting and small or occasionally employed appliances, but in others where electricity is extremely cheap compared with gas or coal one often finds the same circumstances, and this is due to insufficient enterprise and salesmanship on the part of the contractor or electricity supplier. This difficulty is being overcome, and is one in which the architect can help us very much.

Mr. Raphael suggested that I attempted in the paper to introduce too strong a feature of salesmanship into the electricity business. I cannot think that he quite means this, as all my statements are accompanied with limiting figures, and it is the practice to-day to show clearly what can be done, with advantage to the user, in this or that district; not to claim that electricity is universally economical for all purposes but, on the other hand, to restrain the public and even the architect and other non-electrical thinkers from generalizing from limited and insufficient instances. Frequently business which would have given satisfaction to the user as well as to the supplier has been lost because someone in authority has stated that the electrical method "is expensive," and that without any investigation as to local conditions or without taking the trouble to find out from those who sell and have to stand by the electrical service exactly how far, at their current rates, it would pay the consumer to adopt electrification. It must be obvious from the great diversity of prices charged for coal, gas and electricity up and down the country that what is just practicable in one place may be very cheap in another and impossibly dear in a third.

It was obvious from the discussion that a number of members and vistors were interested in the suggested joint committee. I hope it may be possible to pursue this matter. A committee such as I have in mind would in no way supplant the consulting engineer or contractor, or attempt to deal with concrete problems, but should result in a useful interchange of ideas between the two professions, keeping each other advised on the latest progress. Out of this work could also grow some useful educational effort, for the young architect on electricity and for the young electrical engineer on architecture. For example, the reference made by several speakers to the combination of electricity and other heating media, opens a most interesting field of speculation and one which might well be explored by such a committee. I am convinced that as the years go by a great deal of work will be done on these lines, and that it will go far to solve some of the problems now troubling the architect.

One of the architect speakers in the discussion pointed out that it was one thing to advise the client and another to make him take that advice. Electrical engineers also get plenty of that experience and one cannot expect complete success when putting forward proposals which, however beneficial to the client, are perhaps only partly understood by him and will cost him money. Here it is a question, I think, of a little dignified salesmanship ; a study of the psychology of those who employ us, and not the least important essential for carrying conviction to others is that we should be convinced ourselves.

# A MATHEMATICAL DEVELOPMENT OF THE THEORY OF THE MAGNETOMOTIVE FORCE OF WINDINGS.*

By ALBERT E. CLAYTON, D.Sc. (Eng.), Associate Member.

(*Paper received 15th November, 1922.*)

## SUMMARY.

The mathematical theory of the magnetomotive force developed by armature windings is developed and presented in a new manner, and in such a form that it is at once directly applicable not only to the more common cases but also to abnormal cases, such as unbalanced windings, and to pole-changing windings, etc.

An attempt has been made to present the subject matter in simple mathematical language and to give the various series concerned in as simple a form as possible. In general, the conclusions arrived at in the various sections of the paper have been succinctly stated.

The method of treatment adopted is to start from the Fourier series representing the M.M.F. distribution due to a single coil, and to build up from this series the corresponding series for any complete winding. The effect of the value of the coil-span is discussed, it being shown that, in general, a single coil gives rise to an M.M.F. distribution corresponding to the joint effect of all numbers of poles from 2, 4, 6, etc., upwards. The effect of the spread of the coil-side is briefly discussed, and data relating to the various winding factors concerned are given in a simple graphical form applicable to harmonics of all orders, whether odd or even.

The resulting M.M.F. due to a number of coils carrying the same current is then deduced from the effect of a single coil, heteropolar arrangements also being discussed.

In the sections dealing with alternating-current windings, a similar method is employed. It is shown that all types of polyphase windings fall simply into one category, the treatment being perfectly general and directly applicable to all types of windings, whether normal polyphase, full-pitch or chorded, or a winding intended for pole-changing. The effects of higher harmonics in the current wave are discussed, and data relating to the harmonics present in the M.M.F. developed by polyphase windings are given.

## TABLE OF CONTENTS.

Section Page
(I) The magnetomotive force due to a single coil carrying a steady current, in a machine having a uniform air-gap .. .. .. .. 750
(II) The resulting magnetomotive force distribution due to the combined action of two similar coils, displaced by a given angle and carrying the same current .. .. .. .. 759
(III) The resulting magnetomotive force distribution due to the combined action of *m* similar coils having a constant phase displacement between successive coils, and carrying the same current 761
(IV) As above, but for coils uniformly spaced around the armature .. .. .. .. .. 764
(V) The complete multipolar winding .. .. 765
(VI) The resulting magnetomotive force due to a single coil carrying alternating current .. .. 766
(VII) The resulting magnetomotive force due to a number of coils carrying alternating current 767
(VIII) The normal polyphase winding .. .. .. 771
(IX) Pole-changing windings .. .. .. .. 778
(X) The effects of higher harmonics in the current wave, etc. .. .. .. .. .. 782
Appendix .. .. .. .. .. .. 785

## LIST OF SYMBOLS.

$A_p$ = the amplitude of the $2p$-pole M.M.F. component due to a single complete coil carrying a steady current.

$C_p$ = one half of the maximum value of the amplitude of the $2p$-pole M.M.F. component due to a single complete coil carrying an alternating current.

$f_{wp}$ = the winding factor corresponding to the $2p$-pole component.

$f_{sp}$ = slot-width factor corresponding to the $2p$-pole component.

$f_p = f_{wp} \times f_{sp}$ = the total distribution factor corresponding to the $2p$-pole component.

$f'_1$, $f'_3$, etc. = the distribution factors corresponding to the fundamental, third, etc., harmonics of a multipolar system.

$I_a$ = virtual value of the current per conductor.

$K$ = any integer.

$M$ = any integer.

$m$ = number of coils, i.e. the total number on an armature.

$N$ = number of phases of a polyphase winding as defined by the number of complete coils per pair of poles.

$n$ = order of the harmonic of the current wave.

$p$ = order of the M.M.F. harmonic, i.e. in general $p$ denotes also the number of pole-pairs corresponding to any particular M.M.F. component.

$Q$ = number of slots per pair of poles.

$q$ = an integer, and, in particular, $\phi/\psi$.

$s$ = number of slots per coil-side.

$S$ = number of slots on the armature.

$X$ = M.M.F. developed by a single coil, and, if the ampere-turn is taken as the unit of M.M.F., $X$ denotes the ampere-turns developed by the coil.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

$X_{max.}$ = maximum value of the M.M.F. developed by a single coil when carrying an alternating current.
$x$ = value of the M.M.F. at any point on the circumference.
$x_p$ = value of the M.M.F. at any point on the circumference due to the sole action of the $p$th M.M.F. component.
$Z_a$ = total number of conductors on the armature.
$2\alpha$ = mean span of the coil, expressed in "mechanical radians."
$2\alpha_1$ = mean span of the coil, expressed in "electrical radians" based upon the main number of poles.
$2\beta$ = spread of the coil-side, expressed in mechanical radians.
$2\beta_1$ = spread of the coil-side, expressed in electrical radians.
$2\gamma$ = slot-pitch, expressed in mechanical radians.
$2\gamma_1$ = slot-pitch, expressed in electrical radians.
$\delta = (\pi/2) - \alpha$.
$2\lambda$ = slot width, expressed in mechanical radians.
$\theta$ = displacement of a point on the armature from the axis of the coil, expressed in mechanical radians.
$\theta' = \theta + \pi/2$.
$\theta_1$ = displacement of a point on the armature from the axis of the coil, expressed in electrical radians.
$2\psi$ = displacement between two successive coils, expressed in mechanical radians.
$2\phi$ = phase displacement between the currents in successive coils.
$\tau_p$ = pole-pitch corresponding to $2p$ poles.

## INTRODUCTION.

Of recent years, considerable attention has been attracted to the study of the magnetomotive force of armature windings, and a number of very valuable papers on the subject have been published in this country, in the *I.E.E. Journal* and in the *Electrician*. Almost without exception these papers have originated from Dr. Stanley Parker Smith and from the pen of those whose fortune it has been to work under his direction. The present author has also contributed to the literature of the subject. So far, however, the subject has been dealt with from an entirely analytical standpoint, attention being mainly devoted to the analysis of the magnetomotive force established by a normal symmetrical winding. Such methods of treatment are, of course, invaluable for dealing with the more normal problems that arise in the design of alternating-current machinery, but occasions arise when such methods of treatment are insufficient. For example, it is common knowledge that an ordinary drum coil of a given span can be usefully employed in the formation of a winding intended for operation, with certain minor exceptions, with any desired number of poles, a fact of considerable importance in pole-changing windings. The mathematical theory of the magnetomotive force of windings as hitherto developed, starting as it does from the point of view of the completed winding, obscures this fact. In the present paper, therefore, the author develops the mathematical theory of the magnetomotive force of armature windings in such a manner that it can be applied directly not only to the normal straightforward cases but also to abnormal cases—such as unbalanced windings—and to pole-changing windings.

## I. THE MAGNETOMOTIVE FORCE DUE TO A SINGLE COIL CARRYING A STEADY CURRENT, IN A MACHINE HAVING A UNIFORM AIR-GAP.

Consider the case of a machine, e.g. an induction motor or a turbo-alternator, having a uniform air-gap, and a stator wound with a single coil of the "drum" type and spanning an angle* of $2\alpha$ radians, as in Fig. 1. The coil-side is at first assumed to be of negligible spread, and the coil, surface wound.

When a current is passed through the coil, the magnetomotive force set up establishes a magnetic flux linking with the coil. Assuming that the reluctance of the iron parts of the circuit is negligible, the flux distribution in the air-gap, neglecting the effects of fringing, will be as indicated in Fig. 1, and, in the developed wave, by the rectangular wave-form shown in Fig. 2. The ratio of the flux density "inside" the span of the coil to that "outside" is inversely proportional to the corresponding areas carrying the flux, so that if, as in Fig. 2, $X_1$ and $X_2$ represent, respectively, these two densities, then

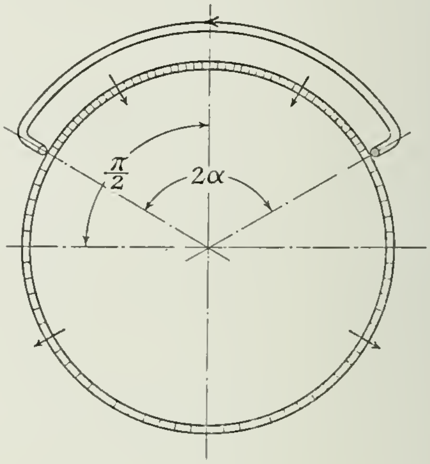


FIG. 1.

$$X_2/\alpha = X_1/(\pi - \alpha)$$

As a result of the current in the coil, a difference of magnetic potential will be established between any point on the stator and the point radially opposite on the rotor. Under the conditions assumed, the wave-shape representing the manner in which this difference of magnetic potential varies around the rotor circumference will be of exactly the same shape as the wave of flux distribution, i.e. as in Fig. 2.

---

* Unless specifically stated to the contrary, the angles referred to in the present paper represent the actual angles concerned, in mechanical radians and not in electrical radians.

On the score of brevity, this wave, representing the manner in which the difference of magnetic potential between stator and rotor varies around the machine, will henceforth be referred to as the magnetomotive force, or M.M.F., distribution wave.

Using now Fig. 2 as this M.M.F. distribution wave, the total magnetomotive force developed by the coil is given by the sum of the values $X_1$ and $X_2$. Thus, if the diagram is plotted with the ampere-turn as the unit of magnetomotive force,

$X = X_1 + X_2 =$ the ampere-turns developed by the coil

The value of the difference of magnetic potential at any point on the circumference may thus be expressed, by means of a Fourier series, in terms of $X$ and the displacement of the point under consideration from any other point on the circumference. A common point to take as origin is one displaced by $\pi/2$ radians from the axis of the coil, as in Fig. 2. Under these conditions the M.M.F. due to a single coil of negligible spread may be represented by the series :—

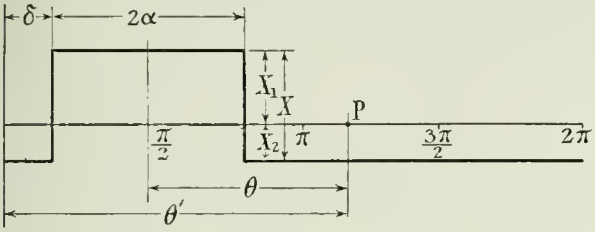


FIG. 2.

$$x = \frac{2X}{\pi}\Big\{(\sin \alpha \sin \theta' - \tfrac{1}{3} \sin 3\alpha \sin 3\theta' + \tfrac{1}{5} \sin 5\alpha \sin 5\theta' - \ldots) - (\tfrac{1}{2} \sin 2\alpha \cos 2\theta' - \tfrac{1}{4} \sin 4\alpha \cos 4\theta' + \tfrac{1}{6} \sin 6\alpha \cos 6\theta' - \ldots)\Big\}. \quad . \quad (1)$$

This may also be written :—

$$x = \frac{2X}{\pi}\Big\{(\cos \delta \sin \theta' + \tfrac{1}{3} \cos 3\delta \sin 3\theta' + \ldots) - (\tfrac{1}{2} \sin 2\delta \cos 2\theta' + \tfrac{1}{4} \sin 4\delta \cos 4\theta' + \ldots)\Big\}^* \quad (2)$$

In the above series

$X$ is the total M.M.F. developed by the coil ;
$2\alpha$ is the span of the coil in mechanical radians (cf. Fig. 1) ;
$x$ is the difference of magnetic potential between stator and rotor at a point distant $\theta'$ radians from the chosen origin, i.e. $\theta' - (\pi/2)$ radians from the axis of the coil (cf. Fig. 2) ; and
$\delta = (\pi/2) - \alpha$.

It follows then that the effect of passing a current through the single coil under consideration is to establish in the air-gap of the machine a magnetic field of such a distribution as to be equivalent to the combined effect of a number of fields corresponding to 2, 4, 6, etc., poles ; these component fields are all of sinusoidal distribution form and of amplitudes and phase relationships as indicated in series (1).

Expressed in the above form, the components corresponding to odd numbers of pole-pairs are all represented by sine terms, and those corresponding to even numbers of pole-pairs are all represented by cosine terms. It therefore becomes more convenient to take as origin a point on the axis of the coil, and to represent the magnetomotive force wave by the series * :—

$$x = \frac{2X}{\pi}(\sin \alpha \cos \theta + \tfrac{1}{2} \sin 2\alpha \cos 2\theta + \tfrac{1}{3} \sin 3\alpha \cos 3\theta + \ldots) \quad . \quad (3)$$

In the above series, $\theta$ is the displacement from the axis of the coil, and $x$ is the difference of magnetic potential between stator and rotor at that point.

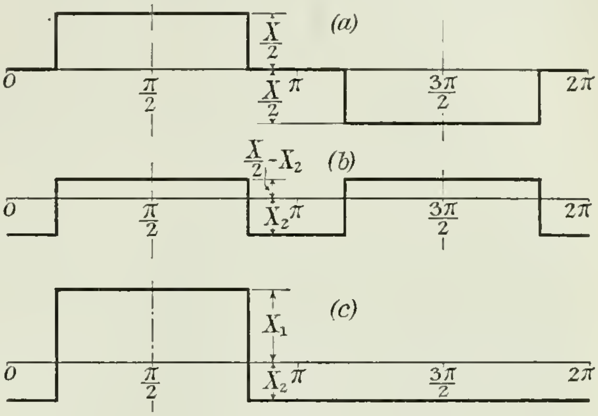


FIG. 3.

It will be noted that in (3) terms involving $\sin \theta$ are absent and, further, that all the terms have the same sign.

The relative magnitudes of the amplitudes of the various components of the M.M.F. wave can therefore readily be deduced from ordinary trigonometrical tables. To indicate the manner in which the values of the various components depend upon the span of the coil, Table 1 has been prepared. In the table the amplitudes of the various components are expressed as a fraction of $X$. The various amplitudes are tabulated against the span of the coil expressed in degrees, i.e. against $2\alpha(180°/\pi)$. The sign denotes the phase of the component at the axis of the coil.

A consideration of the series given in Equation (1) at once indicates that the Fourier series for the M.M.F. established by the single coil naturally subdivides into two separate series, the one containing all the odd terms, and the other all the even harmonics. These component series are :

(1) *For the odd numbers of pole-pairs :—*

$$x' = \frac{2X}{\pi}(\sin \alpha \sin \theta' - \tfrac{1}{3} \sin 3\alpha \sin 3\theta' + \tfrac{1}{5} \sin 5\alpha \sin 5\theta' - \ldots) \quad . \quad (4)$$

---

* Cf. Appendix.

* Cf. Appendix.

(2) *For the even numbers of pole-pairs:*—

$$x'' = -\frac{2X}{\pi}\left(\tfrac{1}{2}\sin 2a\cos 2\theta' - \tfrac{1}{4}\sin 4a\cos 4\theta' + \tfrac{1}{6}\sin 6a\cos 6\theta' - \ldots\right) \quad . \quad (5)$$

The first of these two series, (4), is the Fourier series for the wave-form shown in Fig. 3 (*a*), a wave which, containing only odd harmonics and sine terms, is symmetrical about the 90° axis, and the second half of which forms a true reflection of the first half when displaced by 180°. In fact, the particular wave-form shown in Fig. 3 (*a*) is identical with the M.M.F. wave obtaining for the machine under consideration when wound with two coils of the type shown in Fig. 1, the coils being displaced by 180° and carrying current in opposite directions, the current being one-half of that in the single coil under consideration. Equation (4) thus corresponds to the effect of an ordinary 2-pole winding, having one coil per pole spanning an angle of $2a$, the coil-sides, being of negligible spread, and the total M.M.F. for the two coils of the 2-pole winding being equal to that of the single coil under consideration.

TABLE 1.

*The Values of the Amplitudes of the M.M.F. Components due to a Single Coil having a Side of Negligible Spread.*

| Span of coil, in degrees | Amplitude per ampere-turn for component of order | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 |
| 10 | 0·056 | 0·055 | 0·055 | 0·055 | 0·054 | 0·053 | 0·051 | 0·049 | 0·046 |
| 20 | 0·110 | 0·109 | 0·106 | 0·102 | 0·097 | 0·092 | 0·088 | 0·063 | 0·046 |
| 30 | 0·164 | 0·159 | 0·150 | 0·138 | 0·123 | 0·106 | 0·069 | 0·032 | 0 |
| 40 | 0·217 | 0·204 | 0·184 | 0·157 | 0·125 | 0·092 | 0·027 | – 0·022 | – 0·046 |
| 50 | 0·269 | 0·244 | 0·205 | 0·157 | 0·104 | 0·053 | – 0·027 | – 0·060 | – 0·046 |
| 60 | 0·318 | 0·276 | 0·212 | 0·138 | 0·063 | 0 | – 0·069 | – 0·055 | 0 |
| 70 | 0·365 | 0·299 | 0·205 | 0·102 | 0·011 | – 0·053 | – 0·088 | – 0·011 | 0·046 |
| 80 | 0·409 | 0·314 | 0·184 | 0·055 | – 0·043 | – 0·092 | – 0·051 | 0·041 | 0·046 |
| 90 | 0·450 | 0·318 | 0·150 | 0 | – 0·090 | – 0·106 | 0 | 0·064 | 0 |
| 100 | 0·488 | 0·314 | 0·106 | – 0·055 | – 0·129 | – 0·092 | 0·051 | 0·041 | – 0·046 |
| 110 | 0·521 | 0·299 | 0·055 | – 0·102 | – 0·127 | – 0·053 | 0·088 | – 0·011 | – 0·046 |
| 120 | 0·551 | 0·276 | 0 | – 0·138 | – 0·110 | 0 | 0·069 | – 0·055 | 0 |
| 130 | 0·577 | 0·244 | – 0·055 | – 0·157 | – 0·073 | 0·053 | 0·027 | – 0·060 | 0·046 |
| 140 | 0·598 | 0·204 | – 0·106 | – 0·157 | – 0·022 | 0·092 | – 0·027 | – 0·022 | 0·046 |
| 150 | 0·615 | 0·159 | – 0·150 | – 0·138 | 0·033 | 0·106 | – 0·069 | 0·032 | 0 |
| 160 | 0·627 | 0·109 | – 0·184 | – 0·102 | 0·082 | 0·092 | – 0·088 | 0·063 | – 0·046 |
| 170 | 0·634 | 0·055 | – 0·205 | – 0·055 | 0·104 | 0·053 | – 0·051 | 0·049 | – 0·046 |
| 180 | 0·636 | 0 | – 0·212 | 0 | 0·127 | 0 | 0 | 0 | 0 |

Similarly, the Fourier series (5) represents the wave-form shown in Fig. 3 (*b*), a wave of the same type as the original wave given in Fig. 2, but having the complete wave-length now equal to one-half, instead of the whole, of the circumference. As a result, the series containing solely the even harmonics may, if necessary, further be subdivided. Taking the origin now at the axis of the coil, the series containing the even harmonics may be divided into:—

$$x''' = \frac{2X}{\pi}\left(\tfrac{1}{2}\sin 2a\cos 2\theta + \tfrac{1}{6}\sin 6a\cos 6\theta + \ldots\right) \quad (6)$$

and

$$x'''' = \frac{2X}{\pi}\left(\tfrac{1}{4}\sin 4a\cos 4\theta + \tfrac{1}{8}\sin 8a\cos 8\theta + \ldots\right) \quad (7)$$

Of these series, (6) contains solely all the terms corresponding to fields having a number of poles which is an odd multiple of 4, i.e. to the 4-, 12-, 20-, etc., pole components. Series (7) in a similar manner contains solely those terms corresponding to a number of poles which is an even multiple of 4, i.e. the 8-, 16-, 24-, etc., pole components.

Fig. 3 (*c*) indicates the manner in which the actual M.M.F. wave due to the single coil can be built up graphically from the component waves given in Figs. 3 (*a*) and 3 (*b*).

## THE CONDITION FOR ANY PARTICULAR COMPONENT M.M.F. TO BE ABSENT.

From Equation (3) it follows that when $\sin pa = 0$, the component M.M.F. corresponding to $2p$ poles is absent. For $\sin pa$ to be zero, $pa$ must be zero or any multiple of $\pi$. Hence, when a current is passed through a coil of the type under consideration:—

(1) A 2-pole component field must be established in all cases.

(2) The 4-pole component is absent only when the span of the coil is $\pi$ radians.

(3) The 6-pole component is absent when the coil span $2\alpha = 2\pi/3$ or $4\pi/3$.

(4) The $2p$-pole component is absent when the coil span $2\alpha = 2\pi/p, 4\pi/p, \ldots$ to $[2\pi - (2\pi/p)]$.

Further, if $\sin p\alpha = 0$, it follows that $\sin Mp\alpha = 0$, if $M$ is any integer. Hence, if the span of the coil is such that no component M.M.F. corresponding to $2p$ poles is present, it follows also that no component can be present which has a number of poles equal to a multiple of $2p$.

If $\tau_p$ is the pole-pitch corresponding to $2p$ poles, the condition for there to be no component fields established corresponding to $2p$, or any multiple of $2p$, poles, is thus simply that the span of the coil shall be equal to a multiple of $2\tau_p$. This, of course, is simply the condition that must be fulfilled in order that a field system having $2p$ poles shall be unable to induce an E.M.F. in the coil. In this connection it is well to remember that if a field coil has such a span that it is not capable of producing a component M.M.F. having $2p$ poles, it always follows also that a field system having $2p$ poles cannot induce any E.M.F. in the coil, since it would be impossible for any reaction to be set up by the coil.

As a result, except for the particular case when the span of the coil, $2\alpha$, is such that $2p\alpha$ is a multiple of $2\pi$, a coil spanning an angle of $2\alpha$ radians can be utilized in the formation of a winding for any desired number of poles.

In the case of a complete winding, by distributing the coils around the armature circumference, certain of the component M.M.F.'s present in the M.M.F. wave of the individual coil are entirely eliminated, and the importance of others diminished by the interaction of the various coils. But in no case, whatever method of interconnecting the coils may be employed, is it possible for M.M.F. components to be established of orders that are not present in the M.M.F. wave of the elemental coil* from which the complete winding is evolved.

### THE CONDITION FOR ANY COMPONENT M.M.F. TO HAVE ITS MAXIMUM POSSIBLE VALUE.

The maximum value of the amplitude of the $2p$-pole component of the M.M.F. distribution wave obtains when $\sin p\alpha$ is maximum, i.e. when $\sin p\alpha = \pm 1 \cdot 0$, or $p\alpha$ is equal to any odd multiple of $\pi/2$.

For the maximum value of the $2p$-pole M.M.F. component, the span $2\alpha$ of the coil must thus be equal to any odd multiple of $\pi$ divided by the number of pole-pairs, or, in terms of the pole-pitch $\tau_p$, the span must be $(2M - 1)\tau_p$, $M$ being any integer.

It will be noted that the maximum possible value of the amplitude of the $2p$-pole component varies inversely as the number of poles.

Since if $\sin p\alpha = 1 \cdot 0$, the value of $\sin (2M - 1)p\alpha$ also $= 1 \cdot 0$—whether plus or minus is immaterial—it follows that the span of the coil giving rise to the maximum possible value for the component having $2p$ poles will also give rise to a maximum value for those having $(2M - 1)2p$ poles, i.e. any odd multiple of $2p$ poles.

On the other hand, if $\sin p\alpha = \pm 1 \cdot 0$ it follows that $\sin 2Mp\alpha = 0$. Hence the span of the coil resulting in the maximum value for the $2p$-pole component will result also in the absence of all the components having a number of poles that is any even multiple of $2p$.

As an example, the case of the 18-pole M.M.F. component corresponding to $p = 9$ may be taken. The span of the coil which will give rise to the maximum value of this component is $\pi/9$, $3\pi/9$, $5\pi/9$, $7\pi/9$, $\pi$, $11\pi/9$, $13\pi/9$, $15\pi/9$, or $17\pi/9$. So far as the production of the 18-pole component is concerned, each of the above nine spans is equally effective, although obviously not equally desirable. With any of these above spans, all the components corresponding to odd multiples of 18 poles will have their maximum possible value, but those corresponding to even multiples of 18 poles will be absent.

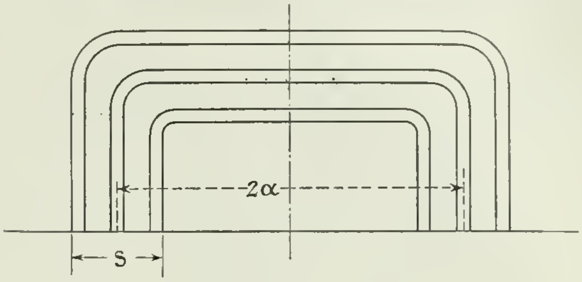


FIG. 4.

### THE MAGNETOMOTIVE FORCE DISTRIBUTION DUE TO A SINGLE COMPLETE COIL.

So far, attention has been confined to the case of a coil of which the sides were of negligible spread. In actual practice, the coil-side is spread over an appreciable portion of the circumference, and may be uniformly distributed, as in the case of surface windings, or distributed in slots as with most modern machines. Further, the actual coil may be constituted of a number of coils having the same axis, but of varying span, i.e. it may be a concentric coil as in Fig. 4, or it may be built up of a number of coils having the same span but arranged with a constant phase displacement between successive coils, forming part of a barrel or lattice winding, as in Fig. 5.

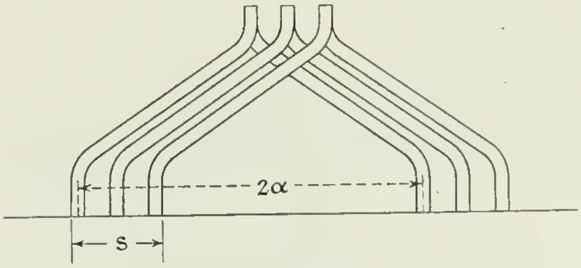


FIG. 5.

---

* For the case of a winding such as an ordinary concentric coil winding, in which the individual turns forming the coil group have not all the same span, the elemental coil referred to above must be regarded as consisting of the complete coil group.

*Case* 1. *Coil side surface-wound.*—The magnetomotive force being distributed uniformly over the width of the coil-side, the M.M.F. distribution around the armature

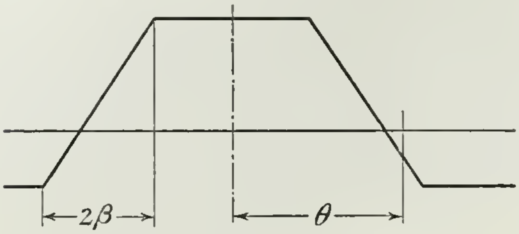


FIG. 6.

is represented by the trapezium wave shown in Fig. 6 instead of the rectangular wave shown in Fig. 2.

The Fourier series representing this particular wave is :—

$$x = \frac{2X}{\pi}\left(\frac{\sin \beta}{\beta} \sin \alpha \cos \theta + \tfrac{1}{2} \times \frac{\sin 2\beta}{2\beta} \sin 2\alpha \cos 2\theta + \tfrac{1}{3} \times \frac{\sin 3\beta}{3\beta} \sin 3\alpha \cos 3\vartheta + \ldots\right) \quad . \quad (8)$$

In the above series

$X$ is the *total* magnetomotive force set up by the coil, i.e. the product of the number of turns and the current (if the ampere-turn is taken as the unit of M.M.F.) ;

$2\beta$ is the spread of the coil-side in actual mechanical radians ; and

$x$ is the difference of magnetic potential between stator and rotor at a point distant by $\theta$ radians from the axis of the complete coil, as in Fig. 6.

Compared with the case of the concentrated coil-side, the Fourier series for which is given in Equation (3), the effect of the spread of the coil-side is to reduce the amplitude of the $2p$-pole component in the ratio $(\sin p\beta)/p\beta$.

This factor is the ordinary " winding factor " or " breadth coefficient " in common use. It is simply the ratio of the sine of one-half the " electrical angle " of spread of the coil-side to the value of one-half of this angle of spread, expressed in electrical radians, the " electrical " angles being based upon $2p$ poles.

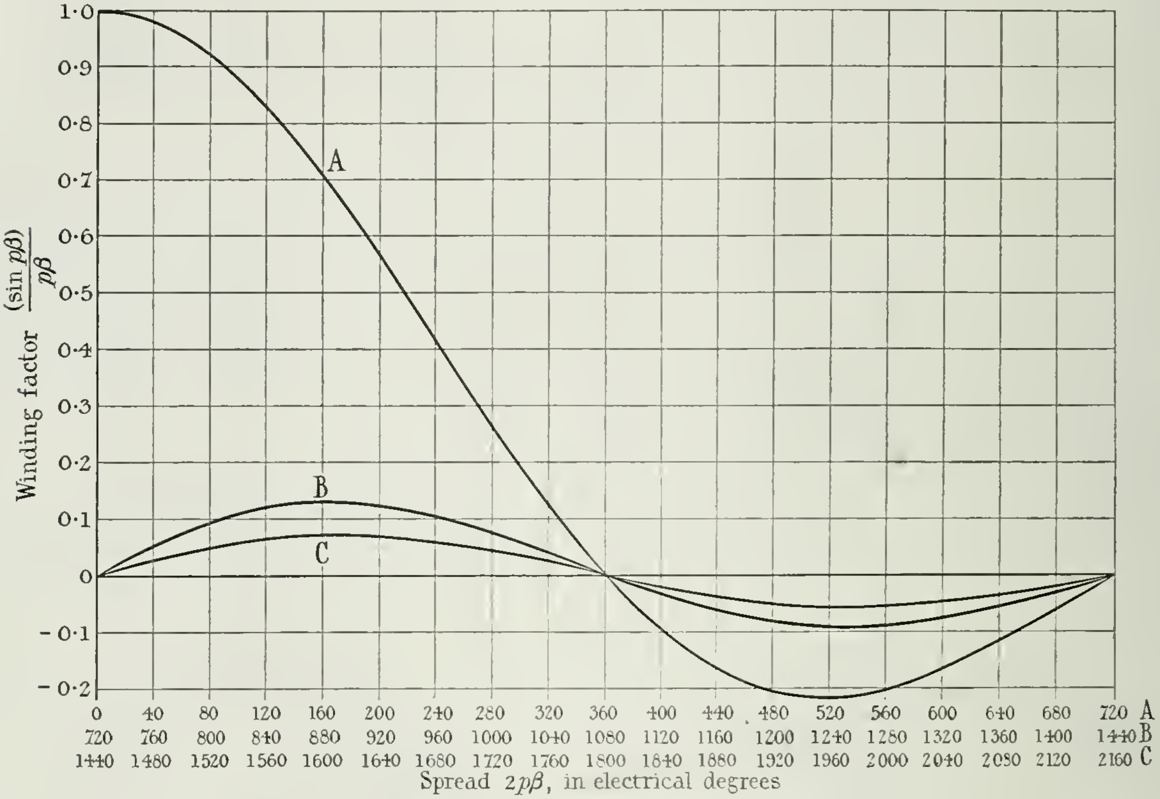


FIG. 7—Winding factors (or breadth coefficients) for surface windings.

The value of the factor is plotted against that of the equivalent spread of the coil side expressed in electrical degrees to correspond to the particular harmonic under investigation.

Values of this factor have been tabulated by various authors, notably by Arnold and Dr. S. P. Smith. The average designer, however, prefers his data to be available in the form of graphs. Fig. 7, from which the value of this breadth coefficient can at once be read off, for any angle of spread of the coil-side and for any value of $p$, has therefore been prepared. The values of the coefficient are plotted as ordinates against the values of $2p\beta \times 180°/\pi$ as abscissæ.

*Case* 2. *Coil-side distributed in slots.*—The effect of distributing the coil-side in slots is to give a stepped form to the M.M.F. distribution wave.

For the case of a barrel winding, in which the component coils are of equal span, the Fourier series representing the resulting M.M.F. distribution may at once be deduced from the series (given later) representing the combined effect of a number of similar coils having a constant phase displacement between successive coils.*

The effect of a concentric winding, so far as the production of the air-gap field is concerned, is identical with that of a barrel winding having the same current distribution, and so may also readily be deduced from Equation (26). The Fourier series for the M.M.F. due to a concentric coil may also be deduced from a consideration of the effects of the individual coils of which it is composed, as shown in Section 5 of the Appendix.

In certain cases, it is sufficiently exact to assume that the width of each individual slot-coil is negligible; this case is therefore first considered.

*Case (a). The M.M.F. due to each component slot-coil assumed to be concentrated at the centre line of the slot.*—Under these conditions the M.M.F. distribution due to a single complete coil, wound in $s$ slots per coil-side, is of the stepped form shown in Fig. 8, the steps being rectangular.

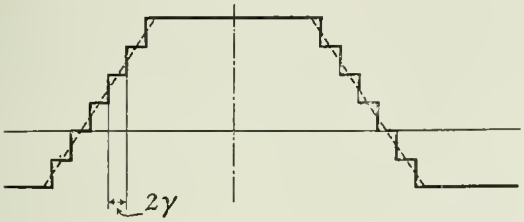


FIG. 8.

In Section 5 of the Appendix it is shown that the Fourier series for this particular wave is :—

$$x = \frac{2X}{\pi}\left(\frac{\sin s\gamma}{s\sin\gamma}\sin\alpha\cos\theta + \tfrac{1}{2}\times\frac{\sin 2s\gamma}{s\sin 2\gamma}\sin 2\alpha\cos 2\theta + \ldots\right) \quad . \quad (9)$$

In the above series, which holds good for both concentric and barrel windings :—

$s$ = the number of slots per coil-side, as in Figs. 4 and 5.

$2\gamma$ = the slot-pitch, expressed in mechanical radians.

Compared with the case of a single concentrated coil developing the same total M.M.F. and having a span $2\alpha$ equal to the mean span of the complete coil under consideration, the effect of distributing the winding in slots, for the conditions at present assumed, is to reduce the amplitude of the field corresponding to $2p$ poles in the ratio of $\sin sp\gamma/(s\sin p\gamma)$. This latter factor is the winding factor or breadth coefficient in common use for dealing with alternating-current windings. Normally it is greater than that for a corresponding smooth armature winding of the same spread, in the ratio of $p\beta/(s\sin p\gamma)$, i.e. of $p\gamma/\sin p\gamma$. Thus the ratio between the two coefficients is independent of the number of slots in which the coil-side is wound, and is determined solely by the angle (in electrical degrees corresponding to the value of $p$) corresponding to the slot-pitch. As a result the winding factor for a slotted armature can readily be deduced from that obtaining for the corresponding smooth armature, by dividing the factor obtaining for a spread of $p\beta$ by that obtaining for a spread of $p\gamma$. From the simple graph given in Fig. 7, the winding factor corresponding to any slotting can thus readily be deduced. Thus, for example, in the case of a coil wound in 6 slots per coil-side in a 96-slot armature, for $p = 4$ the value of $p\beta$ is $\pi/2$, and for $p\gamma$, $\pi/12$. The winding factors for surface windings corresponding to these angles are 0·9003 and 0·988 respectively. Hence the winding factor for the coil under consideration is 0·900/0·988, i.e. 0·911 for $p = 4$.

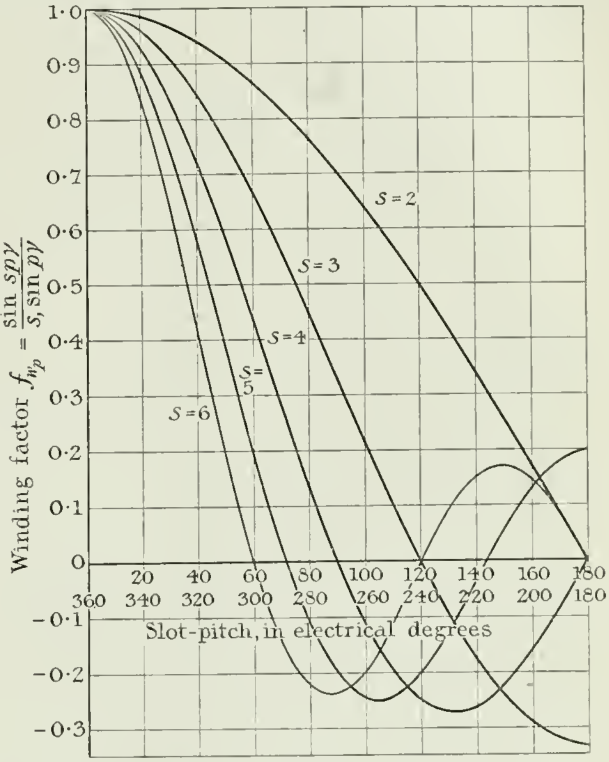


FIG. 9 (*a*).—Winding factors for slotted armatures.

The slot-pitch is expressed in electrical degrees to correspond to the particular harmonic under investigation. The graphs give the numerical values of the factor for the angles indicated and also for $M \times 360°$ plus those angles, $M$ being any integer. When $s$ is an odd number the sign of the factor is always as given in the graph, but when $s$ is even the sign must be reversed for angles between 180° and 540°, 900° and 1 260°, etc.

These winding factors are so much used in alternating-current work (the same factors holding whether the problem concerns the E.M.F. induced in a distributed winding, or the magnetomotive force developed by the winding), that it is desirable to have their values readily available. The values of the factor for various slottings and numbers of phases are tabulated in Arnold's books, and in papers* by various authors. These tables, however, are limited in their application and soon become bulky. Moreover, it is usual to tabulate values of the factors for odd harmonics only, whereas for the case under consideration it is necessary to deal with harmonics of all orders, both odd and even. In addition, it is a convenience to have the data available in the form of a graph. Figs. 9 (*a*) and 9 (*b*) have therefore been prepared by the author; from the graphs there given the value of the winding factor for any harmonic and for all slottings, i.e. whether the total number of slots is divisible by the number of main poles or not, can at once be read off for 2, 3, 4, 5, 6, 8, 10 or 12 slots per coil-side. In these graphs the values of the winding factors are plotted as ordinates against those of the slot-pitch as abscissæ, *the slot-pitch being expressed in electrical degrees to correspond to the particular harmonic under investigation.* The curves hold good for both odd and even harmonics and for any number of phases, and represent simply :—

---

* Cf. Equation (26), p. 762.

* S. P. SMITH and R. H. BOULDING: "The Shape of the Pressure Wave in Electrical Machinery," *Journal I.E.E.*, 1915, vol. 53, p. 218; also B. HAGUE: "Pressure Harmonics in Polyphase Systems and Windings," *Electrician*, 1917, vol. 78, p. 765.

$\sin 2p\gamma/(2 \sin p\gamma)$ for two slots per coil-side ;
$\sin 3p\gamma/(3 \sin p\gamma)$ for three slots per coil-side ;
$\sin 4p\gamma/(4 \sin p\gamma)$ for four slots per coil-side ;

and so on.

To illustrate the use of the curves as applied to a normal complete winding, the case of a three-phase machine with 6 slots per phase and per pole may be taken. The winding factors for all the harmonics of the phase pressure can be read off at once from the graph marked " $s = 6$." For the fundamental the slot-pitch is equivalent to 10 electrical degrees, and hence the winding factor is 0·957. For the third harmonic the slot-pitch is equivalent to 30° and the winding factor is 0·644 ; for the 15th the pitch is equivalent to 150°, and the factor becomes 0·172, and so on. For almost all cases met with in practice, $s$ will not exceed 12,* and the graphs given in Figs. 9(*a*) and 9(*b*) will suffice. For exceptional cases the value of the factor can be deduced from Fig. 7 by the method indicated above. Or it may, in most cases, be deduced from the graphs given in Fig. 9 by dividing the coil into a number of similar parts, in the following manner :—

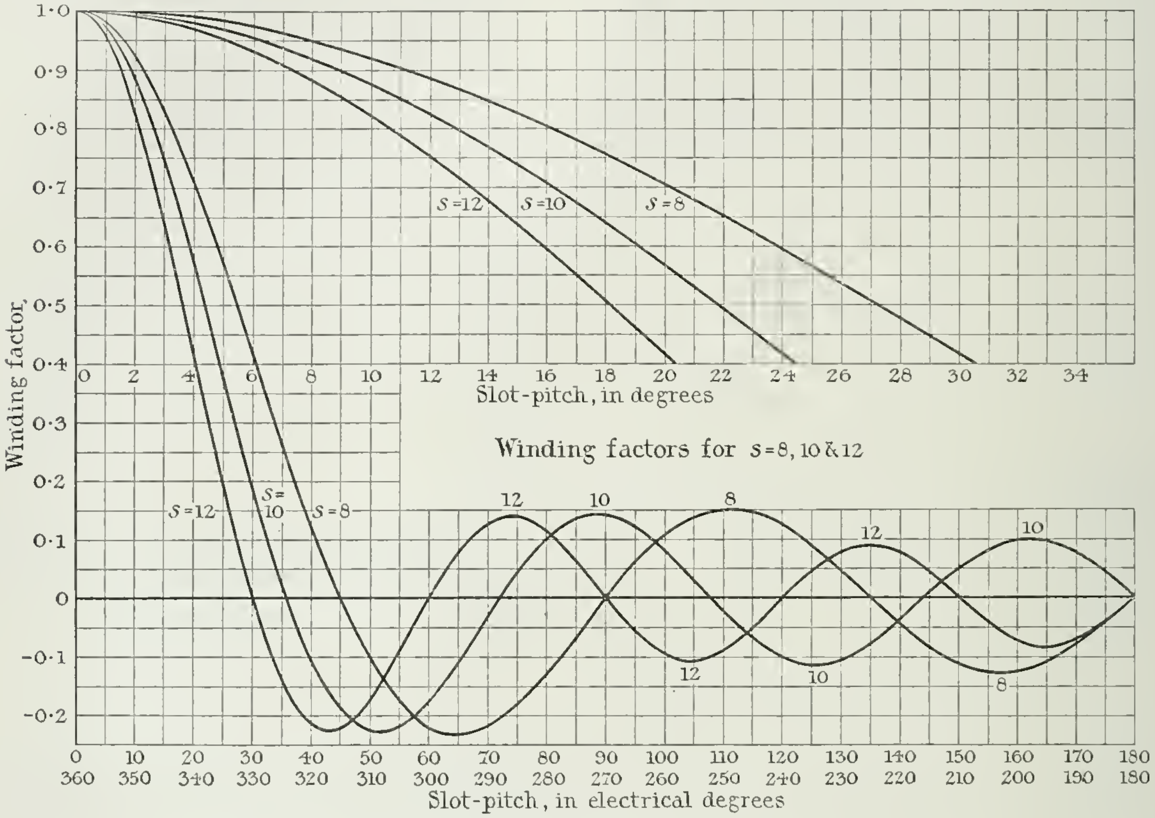


FIG. 9 (*b*).—Winding factors for slotted armatures, for 8, 10 and 12 slots per coil-side.

The graphs give the numerical values of the factor for the angles indicated, and also for $M \times 360°$ plus those angles ; for angles between 180° and 540°, 900° and 1260°, etc., the sign must be reversed.

Let $s = Ms'$, where $M$ is an integer. Then the value of the breadth coefficient for the $p$th harmonic is given by :—

$$\frac{\sin sp\gamma}{s \sin p\gamma} = \frac{\sin s'p\gamma}{s' \sin p\gamma} \times \frac{\sin (Ms'p\gamma)}{M \sin s'p\gamma}$$

The actual coefficient can thus readily be obtained from the product of the two component coefficients. As an example, the case of a 2-pole armature having

---

* In Section 3 of the Appendix, data are tabulated from which graphs for $s = 2, 3, 4, 5, 6, 8, 10$ or 12 can be plotted.

60 slots and $s = 10$ may be taken. The coefficient for the 5th harmonic is then obtained as follows :—

$$2\gamma = 360°/60, \text{ hence } \gamma = 3°$$

Then the required coefficient

$$= \frac{\sin(10p\gamma)}{10\sin p\gamma} = \frac{\sin(10\times 15°)}{10\sin 15°}$$

$$= \frac{\sin(5\times 15°)}{5\sin 15°} \times \frac{\sin 2(5\times 15°)}{2\sin(5\times 15°)}$$

$$= 0{\cdot}746 \times 0{\cdot}259 \text{ (from Fig. 9)}$$

$$= 0{\cdot}193$$

Denoting the various breadth coefficients by $f_{w1}$, $f_{w3}$, etc., the M.M.F. distribution due to the single complete coil under consideration becomes :—

$$x = \frac{2X}{\pi}(f_{w1}\sin a\cos\theta + \tfrac{1}{2}f_{w2}\sin 2a\cos 2\theta + \tfrac{1}{3}f_{w3}\sin 3a\cos 3\theta + \ldots) \quad . \quad (10)$$

*Case (b). The M.M.F. due to each component coil assumed to be distributed uniformly over the slot width.*— Instead of the M.M.F. being concentrated at the centre-line of the slot, it is actually distributed over the copper width of the slot. As a result, the M.M.F. distribution due to the individual slot coil is of the trapezium form shown in Fig. 10 (*a*), in which $2\lambda$ is the copper width per slot, in mechanical radians.*

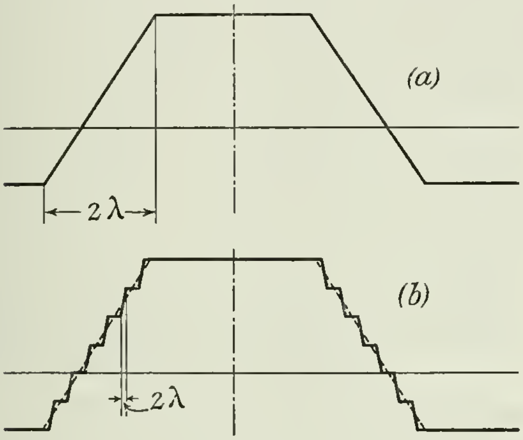


FIG. 10.

The M.M.F. distribution due to the single complete coil arranged in $s$ slots per coil-side is therefore of the stepped form shown in Fig. 10 (*b*), the steps being inclined, instead of vertical. The Fourier series representing the wave-form shown in Fig. 10 (*a*) is, from Equation (8) :—

$$x = \frac{2X}{\pi}\left(\frac{\sin\lambda}{\lambda}\sin a\cos\theta + \tfrac{1}{2}\times\frac{\sin 2\lambda}{2\lambda}\sin 2a\cos 2\theta + \tfrac{1}{3}\times\frac{\sin 3\lambda}{3\lambda}\sin 3a\cos 3\theta + \ldots\right) \quad . \quad (11)$$

The resulting M.M.F. distribution due to the action of the complete coil is therefore represented by :—

$$x = \frac{2X}{\pi}\left(f_{w1}\frac{\sin\lambda}{\lambda}\sin a\cos\theta + \tfrac{1}{2}f_{w2}\frac{\sin 2\lambda}{2\lambda}\sin 2a\cos 2\theta + \ldots\right) \quad . \quad (12)$$

Compared with the previous case, the amplitudes of the various harmonics are reduced by the introduction of the "slot-width factor," $(\sin p\lambda)/p\lambda$.

The values of this slot-width factor for the various components can be read off at once from Fig. 7, which is plotted for the slot width as expressed in electrical degrees corresponding to the particular harmonic under investigation.

Thus for the case when the copper width per slot is 10 mm, the slot pitch 30 mm, and the number of slots per main pole 12 :

For the fundamental, $2\lambda = 5°$, and the slot-width factor $= 1{\cdot}000$.

For the third harmonic, $2p\lambda = 15°$, and the slot-width factor $= 0{\cdot}997$.

For the fifteenth harmonic, $2p\lambda = 75°$, and the slot-width factor $= 0{\cdot}930$.

In a similar manner, with 6 slots per pole and the copper width equal to one-half of the slot-pitch, the slot-width factor for the fundamental would be 0·997, for the third harmonic 0·974, and for the eleventh harmonic 0·688.

In general, the effect of the actual variation of the M.M.F. over the width of the slot is inappreciable so far as the fundamental is concerned. In special machines of very small pole-pitch, however, the effect of this variation is of importance even in the case of the fundamental harmonic.

For the very high harmonics, however, the effect of the distribution of the M.M.F. over the slot width is to reduce their values very considerably below those obtaining for the wave indicated in Fig. 8, the extent of the reduction depending both upon the number of slots per pole for the complete winding and upon the ratio of the slot width to the slot-pitch.

Denoting the slot-width factors by $f_{s1}$, $f_{s2}$, etc., the actual M.M.F. distribution due to the sole action of a single complete coil group distributed in $s$ slots per coil-side, is represented by the series :—

$$x = \frac{2X}{\pi}(f_{s1}f_{w1}\sin a\cos\theta + \tfrac{1}{2}f_{s2}f_{w2}\sin 2a\cos 2\theta + \ldots) \quad (13)$$

The above series may further be simplified by combining the factors $(f_{s1}, f_{w1})$, $(f_{s2}, f_{w2})$, etc., and thus obtaining the true, complete distribution factors for the actual coil group, these true distribution factors taking account both of the spread of the individual coils in the slot and of the spacing of the component coils.

Denoting these true distribution factors by $f_1$, $f_2$, etc., the total M.M.F. distribution due to the single complete coil group may thus be represented by

$$x = \frac{2X}{\pi}(f_1\sin a\cos\theta + \tfrac{1}{2}f_2\sin 2a\cos 2\theta + \tfrac{1}{3}f_3\sin 3a\cos 3\theta + \ldots) \quad . \quad (14)$$

---

* This point has already been discussed by the present author in previous papers. Cf. *Journal I.E.E.*, 1916, vol. 54, p. 94, and 1919, Supplt. to vol. 57, p. 69.

To obtain the various factors $f_1, f_2$, etc., the products of $f_{s1}$ and $f_{w1}$, $f_{s2}$ and $f_{w2}$, etc., as obtained from Figs. 7 and 9 must be taken. In order to be able to read off the factors accurately, it is desirable in the case of the lower harmonics to have the initial portions of the graphs given in Figs. 7 and 9 plotted to a larger scale, as indicated in Figs. 11 and 12.*

It is desirable to investigate the conditions under which the spreading of the coil results in the elimination of any particular component M.M.F. Independent of the mean span of the coil, the $2p$-pole component is eliminated when $f_p = 0$, i.e. when either $f_{wp}$ or $f_{sp} = 0$. The winding factor is zero when $\sin sp\gamma = 0$, provided that $\sin p\gamma$ is not also zero.

Hence the $2p$-pole component M.M.F. is eliminated when $p\gamma = M\pi/s$, where $M/s$ is not an integer. When $p\gamma = M\pi/s$, and $M/s$ *is* an integer, the value of the winding factor is unity.

If the total number of slots on the armature is denoted by $S$, the $2p$-pole component is thus eliminated when $p = MS/s$, provided that $M/s$ is not an integer. For the winding factor to be unity, $p = MS/s$, and $M/s$ is an integer; hence $p$ is simply a multiple of $S$.

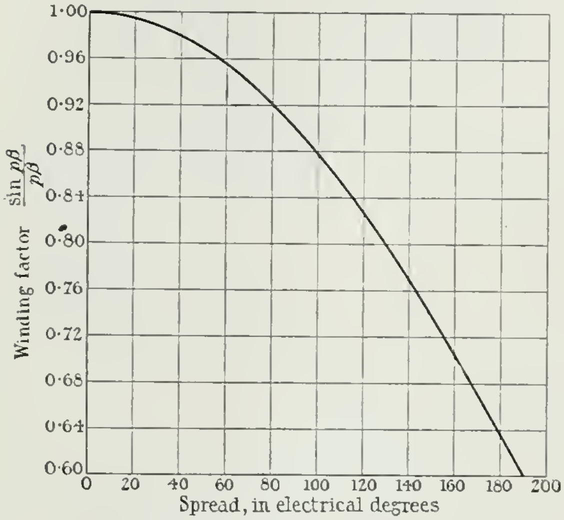


FIG. 11.—Winding factors for surface windings. (This graph may also be used for determining slot-width factors.)

The slot-width factor is zero when $p\lambda = M\pi$, i.e. when $p = M\pi/\lambda$. It is unity only when $p\lambda = 0$, i.e. when $\lambda = 0$, and hence can never be exactly unity in practice.

As a result, independent of the mean span of the coil, the $2p$-pole component M.M.F. is eliminated when $p = MS/s$ (other than when $p =$ a multiple of $S$), and when $p = M\pi/\lambda$.

Normally, then, the effect of spreading the side of the coil over an appreciable portion of the armature circumference is to reduce very considerably the importance of the high harmonics in the M.M.F. distribution wave. The phase displacement between the slots results in a considerable reduction in the importance of certain of the harmonics, but its action is of a selective nature and, generally, the importance of certain series of high harmonics is not reduced. On the other hand, the distribution of the M.M.F. of each slot coil over the width of the slot results in the importance of all the high harmonics being considerably reduced; it is only necessary to inspect the formula $f_{sp} = (\sin p\lambda)/p\lambda$, to verify this.

It is interesting to note that the values of the winding factor $f_{wp}$ repeat periodically as $p$ is increased.* The condition that the winding factor shall have the same numerical value for $p$ pole-pairs as for $p'$ pole-pairs is:—

$$\frac{\sin sp\gamma}{s \sin p\gamma} = \pm \frac{\sin sp'\gamma}{s \sin p'\gamma}$$

$$p'\gamma = M\pi \pm p\gamma \text{ is a solution.}$$

Also $$p' = MS \pm p, \text{ since } \gamma = \pi/S.$$

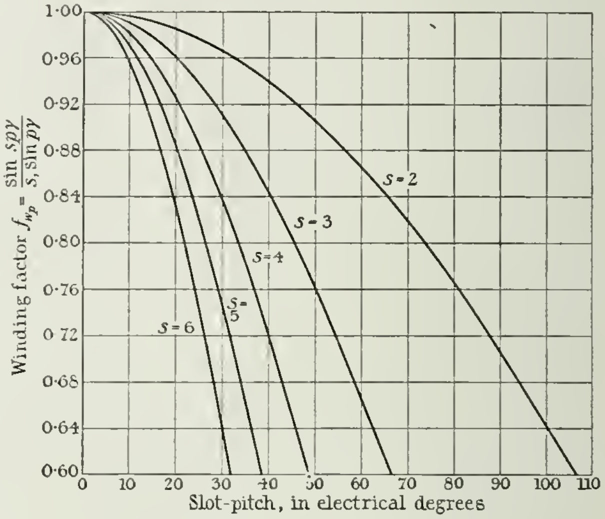


FIG. 12.—Winding factors for slotted armatures.

For the factors to be of the same sign when $s$ is an even number

$$p' = 2MS \pm p$$

and the signs are opposite when

$$p' = (2M - 1)S \pm p$$

These results are indicated by the form of the graphs in Fig. 9. When $s$ is an odd number, the factors will be identical when

$$p' = MS \pm p$$

To illustrate the manner of applying the theory here developed to a practical case, Table 2 has been prepared for the case of a coil wound in three slots per coil-side, and having a mean span of 9 slots in a stator slotted uniformly with 72 slots. (Such a coil would thus be suited to form part of a hemitropic, 8-pole, three-phase winding.)

---

* See also Fig. 9 (*b*).

* Since this paper was written, a valuable paper entitled "The Distribution Factor of Armature Windings," by Messrs. B. Hague and S. Neville, has been published (see *Journal I.E.E.*, 1922, vol. 60, p. 861).

The slot-pitch has been taken to be twice the slot width. For purposes of comparison, the values obtaining for a corresponding surface winding, for a winding in which the slot width is negligible, and for a concentrated winding of negligible spread are also tabulated.

It will be noticed that it is only in the case of the high harmonics that any serious error results from assuming the slot M.M.F. to be concentrated at the centre-line of the slot. For the very high harmonics, however, the effect of the width of the slot is very marked. The sign denotes the phase of the component at the axis of the coil.

TABLE 2.

*The Relative Values of the M.M.F. Components due to a Single Complete Coil wound in 3 Slots per Coil-side, and having a Mean Span of 9 Slot-pitches in a 72-slot Stator.*

The slot-width is taken to be one-half the slot-pitch. $s = 3$; $2\beta = 15°$; $2\alpha = 45°$; $2\gamma = 5°$; $2\lambda = 2\cdot5°$.

| Number of poles | Winding factors, etc. | | | Amplitude of component, per ampere-turn of coil | | | |
|---|---|---|---|---|---|---|---|
| | $\frac{\sin p\beta}{p\beta}$ | $\frac{\sin sp\gamma}{s \sin p\gamma}$ | $\frac{\sin p\lambda}{p\lambda}$ | Concentrated coil | Surface winding | $s = 3$; $\lambda = 0$ | $s = 3$; $2\lambda = 2\cdot5$ |
| 2 | 0·997 | 0·997 | 1·000 | 0·244 | 0·243 | 0·243 | 0·243 |
| 4 | 0·988 | 0·990 | 1·000 | 0·225 | 0·222 | 0·223 | 0·223 |
| 6 | 0·974 | 0·977 | 0·999 | 0·196 | 0·191 | 0·1915 | 0·1915 |
| 8 | 0·955 | 0·960 | 0·999 | 0·159 | 0·152 | 0·1525 | 0·1525 |
| 10 | 0·930 | 0·939 | 0·998 | 0·118 | 0·110 | 0·111 | 0·111 |
| 12 | 0·900 | 0·911 | 0·997 | 0·075 | 0·0675 | 0·0685 | 0·0680 |
| 16 | 0·827 | 0·844 | 0·995 | 0 | 0 | 0 | 0 |
| 20 | 0·738 | 0·762 | 0·992 | − 0·045 | − 0·033 | − 0·0345 | − 0·034 |
| 24 | 0·637 | 0·667 | 0·988 | − 0·053 | − 0·034 | − 0·0355 | − 0·035 |
| 32 | 0·414 | 0·449 | 0·980 | 0 | 0 | 0 | 0 |
| 40 | 0·191 | 0·218 | 0·968 | 0·0318 | 0·0061 | 0·0066 | 0·0065 |
| 48 | 0 | 0 | 0·955 | 0 | 0 | 0 | 0 |
| 56 | − 0·136 | − 0·177 | 0·939 | − 0·0227 | 0·0031 | 0·0040 | 0·0038 |
| 72 | − 0·212 | − 0·333 | 0·900 | 0·0177 | − 0·0038 | − 0·0059 | − 0·0053 |
| 88 | − 0·087 | − 0·177 | 0·853 | − 0·0145 | 0·0014 | 0·0026 | 0·0022 |
| 104 | 0·073 | 0·218 | 0·799 | 0·0122 | 0·0009 | 0·0027 | 0·0021 |
| 120 | 0·127 | 0·667 | 0·738 | − 0·0106 | − 0·0013 | − 0·0071 | − 0·0052 |

The last five values for the numbers of poles correspond respectively to the 7th, 9th, 11th, 13th and 15th harmonics of an 8-pole field system (for which the coil is best suited).

## II. THE RESULTING MAGNETOMOTIVE FORCE DISTRIBUTION DUE TO THE COMBINED ACTION OF TWO SIMILAR COILS, DISPLACED BY A GIVEN ANGLE $2\psi$ AND CARRYING THE SAME CURRENT.

For convenience, the diagrams given will in general correspond to the case of coils of negligible spread of coil-side. The displacements between coils will be measured in the normal counter-clockwise direction.*

*Case* 1. *Coils carrying current in the same direction* (see Fig. 13).—Fig. 13 indicates two coils carrying current in the same direction, i.e. so that each tends to establish a field of the same polarity at the portion of the stator bore spanned by the respective coils. The mechanical phase displacement between the two coils is $2\psi$ radians.

Under the conditions assumed, viz. of negligible reluctance for the iron parts of the magnetic circuit, the resulting effect of the two coils may be obtained by summing their individual effects when acting separately.

Measuring displacements from the axis of coil I, the M.M.F. at any point P distant by $\theta$ radians from the origin, due solely to the action of coil I, is given by :—

$$x' = \frac{2X}{\pi}(f_1 \sin \alpha \cos \theta + \tfrac{1}{2} f_2 \sin 2\alpha \cos 2\theta + \tfrac{1}{3} f_3 \sin 3\alpha \cos 3\theta + \ldots)$$

$$= A_1 \cos \theta + A_2 \cos 2\theta + A_3 \cos 3\theta + \ldots \qquad (15)$$

where $A_1 = \frac{2X}{\pi} f_1 \sin \alpha, \ldots A_p = \frac{2X}{\pi} \times \frac{1}{p} f_p \sin p\alpha$, etc.

Similarly, the M.M.F.* at the point P due to the sole action of coil II is represented by :—

$$x'' = A_1 \cos (\theta - 2\psi) + A_2 \cos 2(\theta - 2\psi) + A_3 \cos 3(\theta - 2\psi) + \ldots \qquad (16)$$

---

* So that if coil A is displaced by $+ 2\psi$ from coil B, coil A is $+ 2\psi$ radians in advance of B in a counter-clockwise direction.

* As stated previously, on the score of brevity, the term M.M.F. is being used instead of "difference of magnetic potential."

The corresponding wave-forms are indicated in Figs. 14 (*a*) and 14 (*b*). The joint effect of the two coils may be obtained graphically, as in Fig. 14 (*c*), or mathematically, by summing the two series (15) and (16).

The resulting M.M.F. distribution is thus represented by the series :—

$$\begin{aligned} x &= x' + x'' \\ &= A_1\left\{\cos\theta + \cos(\theta - 2\psi)\right\} \\ &\qquad + A_2\left\{\cos 2\theta + \cos 2(\theta - 2\psi)\right\} \\ &\qquad\qquad + A_3\left\{\cos 3\theta + \cos 3(\theta - 2\psi)\right\} + \ldots \\ &= 2\left\{A_1 \cos\psi \cos(\theta - \psi) + A_2 \cos 2\psi \cos 2(\theta - \psi) \right. \\ &\qquad \left. + A_3 \cos 3\psi \cos 3(\theta - \psi) + \ldots\right\} \quad . \quad (17) \end{aligned}$$

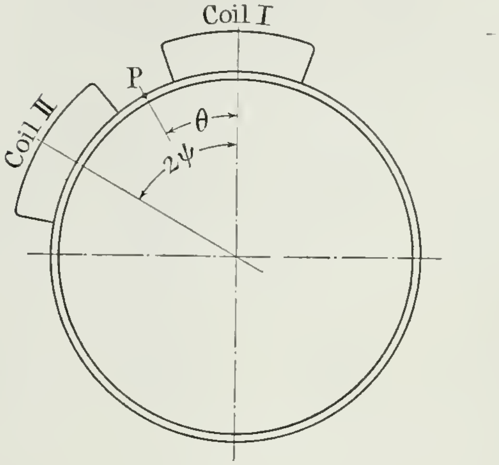


Fig. 13.

The general term, corresponding to the $2p$-pole component, is thus :—

$$x_p = 2A_p \cos p\psi \cos p(\theta - \psi) \quad . \quad . \quad (18)$$

where $A_p$ is the amplitude of the $2p$-pole component in the M.M.F. wave due to the single complete coil. The complete expression for the general term is thus :—

$$x_p = \frac{4X}{\pi} \times \frac{1}{p} f_p \sin p\alpha \cos p\psi \cos p(\theta - \psi) \quad (19)$$

Hence, *so far as the $2p$-pole component of the M.M.F. distribution is concerned, the effects of the two coils are in exact conjunction when* $\cos p\psi = 1 \cdot 0$, i.e. when $2p\psi$ is zero or any even multiple of $\pi$. For example, in the case of the 10-pole component, the effects of the two coils are in conjunction when the displacement between them is $2\psi = 0$, $2\pi/5$, $4\pi/5$, $6\pi/5$ or $8\pi/5$, quite irrespective of the angle $2\alpha$ spanned by the coil. If $\cos p\psi = 1 \cdot 0$, it follows that $\cos Mp\psi = \pm 1 \cdot 0$.

Hence, if the displacement between the two coils is such that the $2p$-pole components of the M.M.F. waves are in conjunction, *all the components corresponding to both odd and even multiples of 2p poles will also be in conjunction.*

On the other hand, irrespective of the span of the coil, *whenever* $\cos p\psi = 0$ *the combined effect of the two coils results in the elimination of the $2p$-pole component* of the M.M.F. For $\cos p\psi$ to be zero, it is necessary that $p\psi$ shall be any odd multiple of $\pi/2$. Thus the 10-pole component is eliminated when $2\psi = \pi/5$, $3\pi/5$, $\pi$, $7\pi/5$ or $9\pi/5$, and the 8-pole component when $2\psi = \pi/4$, $3\pi/4$, $5\pi/4$ or $7\pi/4$.

If $\cos p\psi = 0$ it follows that $\cos(2M - 1)p\psi = 0$, but that $\cos 2Mp\psi = 1 \cdot 0$ or $-1 \cdot 0$.

Hence if the displacement between coils results in the elimination of the $2p$-pole component, it will also result in the *elimination of all the components corresponding to an odd multiple of 2p poles; but all the components corresponding to an even multiple of 2p poles will be in conjunction.*

So that, for example, a phase displacement of $\pi/4$ mechanical radians between the coils will result in the elimination of the M.M.F. components corresponding to 8, 24, 40, 56, etc., poles, and in the production of the maximum possible amplitude, i.e. $2A_p$, for the 16-, 32-, 48-, 64-, etc., pole components.

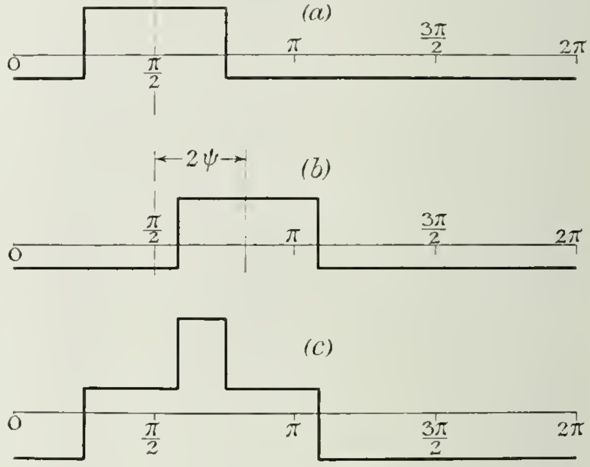


Fig. 14.

*Case 2. Coils carrying current in opposite directions.*— Compared with Case 1, the only difference is that the current in coil II is reversed. The M.M.F. waves for the coils considered separately, and for the resultant effect due to the combined action of the two coils, are therefore as shown in Figs. 15 (*a*), (*b*) and (*c*), respectively.

It will be noticed that under these new conditions flux only crosses the air-gap at the portions of the circumference that are actually embraced by one or other of the two coils. This can, of course, only hold when the iron has negligible reluctance, and when fringing effects are negligible.

The resulting M.M.F. at any point P distant by $\theta$ radians from the axis of coil I, is now given by :—

$$\begin{aligned} x &= x' + x'' \\ &= A_1\left\{\cos\theta - \cos(\theta - 2\psi)\right\} \\ &\qquad + A_2\left\{\cos 2\theta - \cos 2(\theta - 2\psi)\right\} \\ &\qquad\qquad + A_3\left\{\cos 3\theta - \cos 3(\theta - 2\psi)\right\} + \ldots \\ &= 2\left\{A_1 \sin\psi \sin(\psi - \theta) + A_2 \sin 2\psi \sin 2(\psi - \theta) \right. \\ &\qquad \left. + A_3 \sin 3\psi \sin 3(\psi - \theta) + \ldots\right\} \quad . \quad (20) \end{aligned}$$

The general term corresponding to the $2p$-pole component is :—

$$x_p = 2A_p \sin p\psi \sin p(\psi - \theta) \quad . \quad . \quad . \quad . \quad (21)$$

$$= \frac{4X}{\pi} \times \frac{1}{p} f_p \sin p\alpha \sin p\psi \sin p(\psi - \theta) \quad . \quad (22)$$

The amplitude of the $2p$-pole component is thus zero when $\sin p\psi = 0$, i.e. when $p\psi = 0$ or any multiple of $\pi$; it is a maximum when $\sin p\psi = 1 \cdot 0$, i.e. when $p\psi$ is any odd multiple of $\pi/2$.

Hence, so far as the $2p$-pole component is concerned, the effects of the two coils are in conjunction when the displacement $2\psi$ between the two coils is such that $2p\psi$ is equal to any odd multiple of $\pi$ radians. On the other hand, this particular component is eliminated when $2p\psi$ is zero or any even multiple of $\pi$. For example, in the case of the 10-pole component the effects of the two coils are in conjunction when their displacement $2\psi$ is $\pi/5$, $3\pi/5$, $\pi$, $7\pi/5$ or $9\pi/5$, and this particular component is eliminated when $2\psi = 0$, $2\pi/5$, $4\pi/5$, $6\pi/5$ or $8\pi/5$.

TABLE 3.

*The Values of the Amplitudes of the M.M.F. Components due to the Joint Action of Two Similar Coils, as in Table 2, displaced by 90°.*

| No. of poles | Amplitude of component per ampere-turn per coil | |
|---|---|---|
| | Currents in same direction | Currents in opposite directions |
| 2 | 0·344 | 0·344 |
| 4 | 0 | 0·446 |
| 6 | 0·271 | 0·271 |
| 8 | 0·305 | 0 |
| 10 | 0·157 | 0·157 |
| 12 | 0 | 0·136 |
| 16 | 0 | 0 |
| 20 | 0 | 0·068 |
| 24 | 0·070 | 0 |
| 28 | 0 | 0·035 |
| 32 | 0 | 0 |
| 36 | 0 | 0·016 |
| 40 | 0·013 | 0 |
| 44 | 0 | 0·004 |
| 48 | 0 | 0 |

So far as fields corresponding to multiples of $2p$ poles are concerned, if $\sin p\psi = 0$ it follows that $\sin Mp\psi = 0$. Hence if the $2p$-pole M.M.F. component is eliminated, all the higher components corresponding to both odd and even multiples of $2p$ poles are also eliminated.

Further, if $\sin p\psi = \pm 1 \cdot 0$, $\sin (2M - 1)p\psi = \pm 1 \cdot 0$,* and $\sin 2Mp\psi = 0$.

Hence if the phase displacement is such as to give rise to the maximum possible value, $2A_p$, for the amplitude of the resulting $2p$-pole M.M.F., all the M.M.F. components corresponding to an odd multiple of $2p$ poles will also have the maximum possible value, but those corresponding to an even multiple of $2p$ poles will be eliminated.

To illustrate the difference in the resulting M.M.F. obtained with the coils connected in reversed series (as in Case 2) as compared with that obtaining with the coils joined in straight series as in Case 1, Table 3 has been prepared. The table shows the resulting M.M.F. components when two coils similar to that already discussed (cf. Table 2) are displaced by 18 slot-pitches in a 72-slot stator, there being 3 slots per coil-side, and the mean span of the coil being 9 slot-pitches.

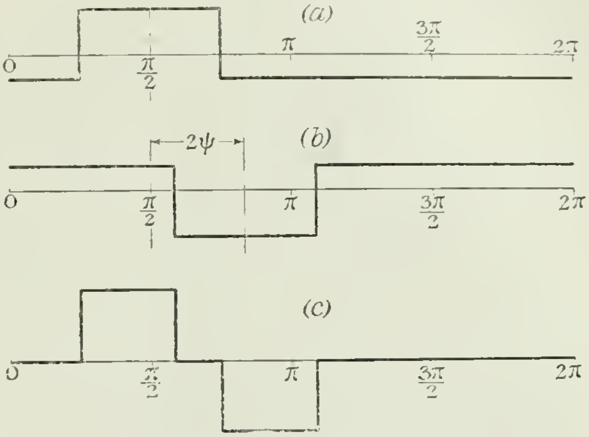


FIG. 15.

These two coils might thus form part of one of the phases of a three-phase induction motor designed to operate with either 8 or 4 poles.

As shown in Table 2, the individual coil, owing to the value of its span, does not produce any component corresponding to a number of poles which is an even multiple of 8.

## III. THE RESULTING MAGNETOMOTIVE FORCE DISTRIBUTION DUE TO THE COMBINED ACTION OF ANY NUMBER, $m$, OF SIMILAR COILS, HAVING A CONSTANT PHASE DISPLACEMENT $2\psi$ BETWEEN SUCCESSIVE COILS, AND CARRYING THE SAME CURRENT.

In a normal complete multipolar winding, the coils in each phase are spaced uniformly around the armature. This particular case is dealt with later, attention being first devoted to the more general case.

*Case 1. Coils all carrying current in the same direction.*—Fig. 16 indicates the arrangement for the case of coils of negligible spread.

The following series represent, respectively, the values of the difference of magnetic potential between stator and rotor at the point P due solely to the action of the various coils :—

$$x' = A_1 \cos \theta + A_2 \cos 2\theta + A_3 \cos 3\theta + \ . \ . \ .$$

$$x'' = A_1 \cos (\theta - 2\psi) + A_2 \cos 2(\theta - 2\psi) + A_3 \cos 3(\theta - 2\psi) + \ . \ . \ .$$

$$x''' = A_1 \cos (\theta - 4\psi) + A_2 \cos 2(\theta - 4\psi) + A_3 \cos 3(\theta - 4\psi) + \ . \ . \ .$$

etc.

---

* Whether plus or minus is immaterial.

The total effect due to the combined action of all the $m$ coils is obtained by summing the effects due to the sole action of the individual coils, and becomes :—

$$
\begin{aligned}
x &= x' + x'' + x''' + \ldots \text{to } m \text{ terms} \\
&= \Big\{ A_1[\cos\theta + \cos(\theta - 2\psi) + \ldots + \cos(\theta - \overline{m-1}\,2\psi) \\
&\quad + A_2(\cos 2\theta + \cos 2(\theta - 2\psi) + \ldots + \cos 2(\theta - \overline{m-1}\,2\psi) \\
&\quad + A_3(\cos 3\theta + \cos 3(\theta - 2\psi) + \ldots + \cos 3(\theta - \overline{m-1}\,2\psi) \\
&\quad + \ldots \qquad\qquad + \ldots \qquad ]\Big\} \\
&= A_1 \frac{\sin m\psi}{\sin\psi} \cos[\theta - (m-1)\psi] \\
&\qquad + A_2 \frac{\sin 2m\psi}{\sin 2\psi} \cos 2[\theta - (m-1)\psi] \\
&\qquad\quad + A_3 \frac{\sin 3m\psi}{\sin 3\psi} \cos 3[\theta - (m-1)\psi] + \ldots \quad (23)
\end{aligned}
$$

The general term corresponding to the $2p$-pole component is thus :—

$$x_p = A_p \frac{\sin pm\psi}{\sin p\psi} \cos p[\theta - (m-1)\psi] \quad . \quad (24)$$

i.e.

$$x_p = \frac{2X}{\pi} \times \frac{1}{p} f_p \sin pa \frac{\sin pm\psi}{\sin p\psi} \cos p[\theta - (m-1)\psi] \quad (25)$$

By taking a fresh origin midway between the axes of the first and the last coil (i.e. displaced by $(m-1)\psi$ radians from the axis of coil 1), the series for the M.M.F. at any point distant by $\theta'$ radians from this new origin reduces to :—

$$
\begin{aligned}
x = A_1 \frac{\sin m\psi}{\sin\psi} \cos\theta' + A_2 \frac{\sin 2m\psi}{\sin 2\psi} \cos 2\theta' \\
+ A_3 \frac{\sin 3m\psi}{\sin 3\psi} \cos 3\theta' + \ldots \quad . \quad (26)^*
\end{aligned}
$$

The amplitude of the general term is thus :—

$$mA_p \frac{\sin pm\psi}{m \sin p\psi} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

$$= \frac{2X}{\pi} \times \frac{m}{p} f_p \sin pa \frac{\sin pm\psi}{m \sin p\psi} \quad . \quad . \quad (28)$$

The factor $(\sin pm\psi)/(m \sin p\psi)$ is the " distribution factor " for the $m$ complete coil groups. Its value can be read off at once from Figs. 9 ($a$) and 9 ($b$).

When $p\psi = 0$ or any multiple of $\pi$, the factor will be unity, and the effects of the various coils will be in exact conjunction so far as the production of the $2p$-pole component M.M.F. is concerned. In addition, all components corresponding to any multiple of $2p$ poles will be in conjunction. Under these conditions the amplitude of the resulting $2p$-pole M.M.F. will be $mA_p$.

On the other hand, when $p\psi$ is not zero or a multiple of $\pi$, but nevertheless $mp\psi$ *is* a multiple of $\pi$, the factor is zero, and the combined effect of all the $m$ coils is to eliminate the $2p$-pole component.

*The condition for the $2p$-pole component to have the maximum value of $mA_p$ is thus $\psi = \pi M/p$.*

*For the $2p$-pole component to be eliminated $\psi = \pi M/(mp)$, where $M/m$ is not an integer.*

So far as the components corresponding to multiples of $2p$ poles are concerned, e.g. to $2Kp$ poles, $K$ being any integer, if the $2p$-pole component is a maximum it follows also that the $2Kp$-pole components will also be a maximum. On the other hand, if the $2p$-pole component is eliminated, the component corresponding to $2Kp$ poles is not always eliminated. It is eliminated for all values of $K$ other than those which make $KM$ a multiple of $m$. For these latter cases the $2Kp$-pole components will be in exact conjunction.

As an example the case of 6 coils, i.e. $m = 6$, may be taken, and the conditions relating to the 16-pole component, $p = 8$, investigated.

The 16-pole component will have the maximum possible value of $6A_{16}$ when the displacement between successive coils is 45°, 90°, 135°, 180°, 225°, 270° or 315°. That is, the displacement must correspond to any multiple of $2\pi/8$. This particular component is eliminated if $2\psi = 7{\cdot}5°$, 15°, 22·5°, 30°, or 37·5°, or any of these angles added to the above seven angles, 45°, etc.

The 32-pole component is a maximum when $2\psi = 22{\cdot}5°$, 67·5°, 112·5°, etc., in addition to 45°, 90°, etc., as indicated in tabular form below. It will be noticed that if the M.M.F. component of the $p$th order is eliminated, all the components of orders $Mmp$ will be in conjunction.

| Order of M.M.F. component $p =$ | Amplitude of resultant component M.M.F. for displacement of | | | | | |
|---|---|---|---|---|---|---|
| | 7·5°, 52·5°, 97·5°, etc. | 15°, 60°, etc. | 22·5°, 67·5°, etc. | 30°, 75°, etc. | 37·5°, 82·5°, etc. | 45°, 90°, etc. |
| 8, 56, 104, etc... | 0 | 0 | 0 | 0 | 0 | Max. |
| 16, 64, 112, etc... | 0 | 0 | Max. | 0 | 0 | Max. |
| 24, 72, 120, etc... | 0 | Max. | 0 | Max. | 0 | Max. |
| 32, 80, 128, etc... | 0 | 0 | Max. | 0 | 0 | Max. |
| 40, 88, 136, etc... | 0 | 0 | 0 | 0 | 0 | Max. |
| 48, 96, 144, etc... | Max. | Max. | Max. | Max. | Max. | Max. |

*Case 2. Adjacent coils carrying current in opposite directions.*—Attention will be confined to the case in which the total number of coils, $m$, is an even number.

The phase displacement between adjacent coils will be taken as $2\psi$ radians, so that the displacement between successive coils carrying current in the same direction is now $4\psi$.

Dividing the coils into two groups, each of $n$ coils

---

* As stated previously (see page 755), the Fourier series for a coil of the lattice or barrel type, built up of $s$ component coils all having the same span, and displaced by a slot-pitch $2\gamma$, follows at once from (26).

The total M.M.F. for the complete coil being represented by $X$, the M.M.F. per component coil is equal to $X/s$. The resulting M.M.F. due to the complete coil, for the case when the M.M.F. per slot is assumed concentrated at the centre-line of the slot, is thus :—

$$
\begin{aligned}
x &= \frac{2}{\pi} \times \frac{X}{s} \left( \sin a \frac{\sin s\gamma}{\sin\gamma} \cos\theta' + \tfrac{1}{2} \sin 2a \frac{\sin 2s\gamma}{\sin 2\gamma} \cos 2\theta' + \ldots \right. \\
&= \frac{2X}{\pi} \left( \frac{\sin s\gamma}{s \sin\gamma} \sin a \cos\theta' + \tfrac{1}{2} \frac{\sin 2s\gamma}{s \sin 2\gamma} \sin 2a \cos 2\theta' + \ldots \right)
\end{aligned}
$$

(where $2n = m$), the one tending to produce north polarity at the portions of the stator bore spanned by the various coils, and the other, south polarity, the M.M.F. distribution waves for these two groups when acting separately may be deduced from (26), and the formula becomes :—

$$x_1' = A_1 \frac{\sin 2n\psi}{\sin 2\psi} \cos \theta' + A_2 \frac{\sin 4n\psi}{\sin 4\psi} \cos 2\theta' + \ldots$$

and

$$x_2' = -\left\{A_1 \frac{\sin 2n\psi}{\sin 2\psi} \cos(\theta' - 2\psi) + A_2 \frac{\sin 4n\psi}{\sin 4\psi} \cos 2(\theta' - 2\psi) + \ldots\right\}$$

respectively.

In these expressions, $x_1'$ and $x_2'$ are the values of the difference of magnetic potential between stator and rotor at a point distant by $\theta'$ radians from an origin displaced by $(n-1)2\psi$ radians from the axis of coil I, and hence distant by $\theta'$ radians from the axis of the $n$th coil.

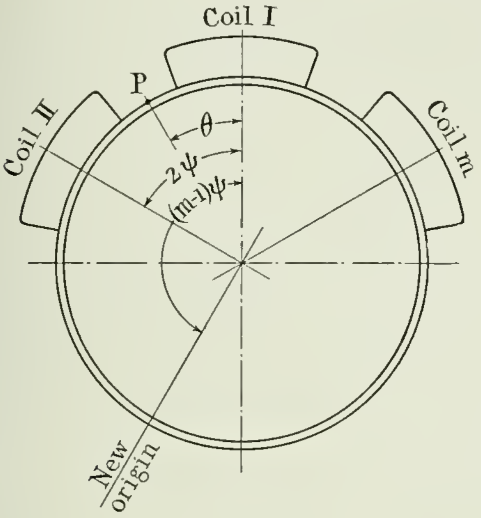


FIG. 16.

The resulting M.M.F. due to the combined action of all the coils is therefore represented by :—

$$\begin{aligned} x &= x_1' + x_2' \\ &= A_1 \frac{\sin 2n\psi}{\sin 2\psi}\{\cos\theta' - \cos(\theta' - 2\psi)\} \\ &\quad + A_2 \frac{\sin 4n\psi}{\sin 4\psi}\{\cos 2\theta' - \cos 2(\theta' - 2\psi)\} + \ldots \\ &= -\left\{A_1 \frac{\sin 2n\psi}{\cos\psi} \sin(\theta' - \psi) + A_2 \frac{\sin 4n\psi}{\cos 2\psi} \sin 2(\theta' - \psi) + \ldots\right\} \quad (29) \\ &= -\left\{A_1 \frac{\sin m\psi}{\cos\psi} \sin(\theta' - \psi) + A_2 \frac{\sin 2m\psi}{\cos 2\psi} \sin 2(\theta' - \psi) + \ldots\right\} \quad (30) \end{aligned}$$

The general term is :—

$$x_p = -A_p \frac{\sin mp\psi}{\cos p\psi} \sin p(\theta' - \psi) \quad . \quad . \quad . \quad . \quad . \quad (31)$$

$$= -\frac{2X}{\pi} \times \frac{1}{p} \times f_p \sin p\alpha \frac{\sin mp\psi}{\cos p\psi} \sin p(\theta' - \psi) \quad . \quad (32)$$

The amplitude of the $2p$-pole component is thus :—

$$mA_p \frac{\sin mp\psi}{m \cos p\psi}$$

The factor $(\sin mp\psi)/(m \cos p\psi)$ is thus of the nature of a distribution factor, its limiting values being numerically zero and unity.* Its value is unity when $p\psi$ = any odd multiple of $\pi/2$, and zero when $mp\psi$ = any multiple of $\pi$, excepting for such cases as would make $p\psi$ an odd multiple of $\pi/2$.

Hence, when $2\psi = (2M - 1)(\pi/p)$, the $2p$-pole component has the maximum possible value of $mA_p$. Under this condition, all the components corresponding to odd multiples of $2p$ poles will also be in conjunction and have their maximum possible value, but the components corresponding to even multiples of $2p$ poles will be eliminated. This elimination of the components corresponding to even multiples of $2p$ poles is noteworthy.

On the other hand, when $2\psi = 2M\pi/(mp)$, the value of $M$ being any integer other than those which make $2M/m$ an odd number, the $2p$-pole component is eliminated. It follows also that if the $2p$-pole component is eliminated, all components corresponding to multiples of $2p$ poles will also be eliminated, excepting those for which $p'\psi$ = an odd multiple of $\pi/2$.

Take as an example the case of $m = 6$, and, as in Case 1, investigate the conditions relating to the 16-pole component. This component now has its maximum possible value of $6A_8$ when the displacement between successive coils is 22·5°, 67·5°, 112·5°, 157·5°, and the corresponding supplementary angles. For the component to be eliminated, $2\psi$ = 7·5°, 15°, 30°, 37·5°, 45°, 52·5°, 60°, etc. The amplitudes of the various harmonics corresponding to multiples of 16 poles are indicated in tabular form below.

| Order of M.M.F. component $p$ = | Amplitude of resultant component M.M.F. for displacement of | | | | | |
|---|---|---|---|---|---|---|
| | 7·5°, 52·5°, 97·5°, etc. | 15°, 60°, etc. | 22·5°, 67·5° etc. | 30°, 75°, etc. | 37·5°, 82·5°, etc. | 45°, 90°, etc. |
| 8, 56, 104, etc... | 0 | 0 | Max. | 0 | 0 | 0 |
| 16, 64, 112, etc... | 0 | 0 | 0 | 0 | 0 | 0 |
| 24, 72, 120, etc... | Max. | 0 | Max. | 0 | Max. | 0 |
| 32, 80, 128, etc... | 0 | 0 | 0 | 0 | 0 | 0 |
| 40, 88, 136, etc... | 0 | 0 | Max. | 0 | 0 | 0 |
| 48, 96, 144, etc... | 0 | 0 | 0 | 0 | 0 | 0 |

These results should be contrasted with those obtaining for the previous case, when all the coils carry current in the same direction.

---

* $m$ is here an even number.

## IV. The Resulting Magnetomotive Force due to the Combined Action of Any Number, $m$, of Similar Coils, Uniformly Spaced around the Armature and carrying the Same Current.

*Case* 1. *Coils carrying current in the same direction.*—The phase displacement between adjacent coils is now $2\psi = 2\pi/m$, i.e. $\psi = \pi/m$. The complete winding is thus of the nature of a stator winding having one coil per pole-pair for each phase.

The general term in the series for the resulting M.M.F. is obtained at once from (25) and (26) by replacing $\psi$ by $\pi/m$, and becomes :—

$$x_p = A_p \frac{\sin p\pi}{\sin p(\pi/m)} \cos p[\theta - \overline{m - 1}(\pi/m)]$$

The resulting amplitude of the $2p$-pole component is thus $mA_p \frac{\sin p\pi}{m \sin p(\pi/m)}$. Since $p$ is of necessity an integer, $\sin p\pi = 0$. As a result, the component M.M.F. corresponding to $2p$ poles is eliminated for all cases where $\sin p\pi/m$ has any value other than zero, i.e. for all cases in which $p$ is not a multiple of $m$.

Hence, with $m$ similar coils arranged symmetrically around an armature and carrying equal currents in the same direction :—

(1) All the M.M.F. components having a smaller number of poles than $2m$ are eliminated ;
(2) Of the higher components, only those having a number of poles which is some multiple of $2m$ can be present ; and
(3) Components may be present corresponding to an even multiple of $2p$ poles.

For the case when $p$ is a multiple of $m$ and equal to $Mm$, the resulting amplitude of the $2p$-pole component becomes :—

$$mA_p = m\frac{2X}{\pi} \times \frac{1}{p} \times f_p \sin pa \quad . \quad . \quad (33)$$

The general term in the series for the resulting M.M.F. is thus :—

$$\begin{aligned} x_p &= mA_p \cos p\left[\theta - \overline{m - 1}\left(\frac{\pi}{m}\right)\right] \frac{\sin p\pi}{m \sin p(\pi/m)} \\ &= mA_p \cos p\theta \\ &= m\frac{2X}{\pi} \times \frac{1}{p} \times f_p \sin pa \cos p\theta \quad . \quad . \quad . \quad (34) \end{aligned}$$

Series (33) and (34) hold for all values of $p$ which are multiples of $m$, and for both odd and even values of $m$.

The Fourier series for the resulting M.M.F. at any point distant by $\theta$ radians from the axis of one of the coils is therefore :—

$$\begin{aligned} x &= m\left\{A_m \cos m\theta + A_{2m} \cos 2m\theta + A_{3m} \cos 3m\theta + \ldots\right\} \\ &= \frac{2X}{\pi}\left\{f_m \sin ma \cos m\theta + \tfrac{1}{2}f_{2m} \sin 2ma \cos 2m\theta \right. \\ &\qquad \left. + \tfrac{1}{3}f_{3m} \sin 3ma \cos 3m\theta + \ldots\right\} \quad (35) \end{aligned}$$

It will be noticed that this series for the resulting M.M.F. due to $m$ similar coils uniformly spaced around the armature and carrying equal currents in the same direction, is of exactly the same type as that obtained in (10) for the complete individual coil group, with the exception that $\theta$ in (10) is replaced by $m\theta$ in (35), and $a$ by $ma$. In both cases $X$ represents the total M.M.F. developed by the individual coil group.

In short, the angles in this last series (35) are now expressed in electrical radians corresponding to $2m$ main poles, the displacement of $2\psi = 2\pi/m$ mechanical radians correspouding to $2\pi$ electrical radians between adjacent coils, for the case of $m$ pole-pairs.

If $2ma$ is not a multiple of $\pi$, even harmonics, in terms of $2m$ poles as the fundamental, will be present in all cases.

If $ma$ is a multiple of $\pi$, the winding develops no M.M.F. whatever, and if $ma$ is an odd multiple of $\pi/2$, only components corresponding to odd multiples of $m$ pole-pairs are present.

*Case* 2. *Adjacent coils carrying current in opposite directions.*—The winding now corresponds exactly to a normal multipolar single-phase winding having one coil per pole.

Taking the same symbols as previously, i.e. $m = 2n$, the displacement between adjacent coils is again $2\psi = 2\pi/m$, i.e. $\psi = \pi/m$. The general term in the series for the resulting M.M.F. is thus, from (31) and (32) :—

$$\begin{aligned} x_p &= -A_p \frac{\sin p\pi}{\cos p(\pi/m)} \sin p(\theta' - \psi) \text{ where } \theta' = (\theta - \overline{n - 1}\ 2\psi) \\ &= A_p \frac{\sin p\pi}{\cos p(\pi/m)} \sin p\left(\overline{m - 1} \times \frac{\pi}{m} - \theta\right) \end{aligned}$$

Again, the resulting M.M.F. is zero for all the components which are not multiples of $2p$ poles. In the present case all components for which $\cos p\pi/m$ is not zero are eliminated.

For $\cos p\pi/m$ to be zero, $p\pi/m$ must be some odd multiple of $\pi/2$, and *hence $p$ must be some odd multiple of $m/2$*.

Hence, with the particular arrangement of coils under consideration :—

(1) All M.M.F. components having a smaller number of poles than $m$ (the number of coils) are eliminated.
(2) Only those components can be present for which the number of poles is an odd multiple of the number of coils.

For the particular case when $p = (2M - 1)(m/2)$, the resulting amplitude of the $2p$-pole component becomes :—

$$mA_p = m\frac{2X}{\pi} \times \frac{1}{p} \times f_p \sin pa \quad . \quad . \quad (36)$$

The general term in the series for the resulting M.M.F. is thus :—

$$\begin{aligned} x_p &= m A_p \frac{\sin p\pi}{m \cos p(\pi/m)} \sin p\left(\overline{m - 1} \times \frac{\pi}{m} - \theta\right) \\ &= mA_p \cos p\theta \qquad [\text{since } p = (2M - 1)(m/2)] \\ &= m\frac{2X}{\pi} \times \frac{1}{p} \times f_p \sin pa \cos p\theta \quad . \quad . \quad . \quad . \quad (37) \end{aligned}$$

The above series (36) and (37) hold for $p = (2M - 1)(m/2)$.

The Fourier series for the resulting M.M.F. at any point distant by $\theta$ radians from the axis of coil I is therefore :—

$$x = m\Big\{A_{m/2}\cos\tfrac{1}{2}m\theta + A_{3m/2}\cos\tfrac{1}{2}3m\theta + A_{5m/2}\cos\tfrac{1}{2}5m\theta + \ldots\Big\}$$

$$= \frac{4X}{\pi}\Big\{f_{m/2}\sin\tfrac{1}{2}ma \times \cos\tfrac{1}{2}m\theta + \tfrac{1}{3}f_{3m/2}\sin\tfrac{1}{2}3ma \times \cos\tfrac{1}{2}3m\theta + \ldots\Big\} \quad (38)$$

This series is of exactly the same general type as that given in (4), with the exception that $\theta$ is replaced by $m\theta/2$, and $a$ by $ma/2$, the angles in (38) being now measured in electrical radians corresponding to $m$ main poles.

It will be noticed that the fundamental harmonic of this arrangement of coils corresponds to one-half of the number of poles obtaining for the fundamental in the previous case, for any given value of $m$.

## V. THE COMPLETE, SYMMETRICAL, MULTIPOLAR WINDING.

The series for the M.M.F. distribution of a normal complete winding, whether of the one-coil-per-pole type, or hemitropic, follows at once from those derived in the previous section.

*One-coil-per-pole winding.*—This type of winding is invariably used for the rotors of turbo-alternators, and for single-phase and two-phase stator windings. It is also much used for the stator windings of three-phase machines of large pole-pitch.

With this type of winding the mean span of the coil may have any desired value, and the M.M.F. distribution due to the complete phase group of the winding is, as given in (38) :—

$$x = \frac{4X}{\pi}\Big\{f_{m/2}\sin\tfrac{1}{2}ma \times \cos\tfrac{1}{2}m\theta + \tfrac{1}{3}f_{3m/2}\sin\tfrac{1}{2}3ma \times \cos\tfrac{1}{2}3m\theta + \ldots\Big\} \quad (38)$$

In the above series

$x$ = the difference of magnetic potential between stator and rotor, expressed in ampere-turns, at the point P.

$X$ = the total M.M.F. per coil as measured by the product of the number of turns (i.e. slots per coil-side × number of conductors per slot), and the current per conductor, the M.M.F. being thus expressed in ampere-turns.

$m$ = the total number of coil groups in the complete phase.

$\theta$ = the displacement of any point P on the armature from the axis of one of the coils, measured in actual mechanical radians.

$a$ = the span of the mean turn of the coil group, measured in mechanical radians.

$f_p$ = the total distribution factor for the $p$th harmonic due to the spread of the coil-side, its value being given by the product of the winding factor $f_{wp} = \dfrac{\sin sp\gamma}{s\sin p\gamma}$, and the slot-width factor $f_{sp} = \dfrac{\sin p\lambda}{p\lambda}$.

*Hemitropic winding.*—With this winding, all the coils in the same phase carry current in the same direction, and it is imperative, if even harmonics are to be avoided, that the mean span of the coil group shall correspond to the normal value of the pole-pitch.

Under these conditions, the value of the M.M.F. at any point is obtained from (35) by replacing $2a$ by $\pi/m$, and is represented by the series :—

$$x = \frac{2X}{\pi}\Big\{f_m\sin\tfrac{1}{2}\pi \times \cos m\theta + \tfrac{1}{2}f_{2m}\sin\pi\cos 2m\theta + \tfrac{1}{3}f_{3m}\sin\tfrac{1}{2}3\pi \times \cos 3m\theta + \ldots\Big\}$$

$$= \frac{2X}{\pi}\Big\{f_m\cos m\theta - \tfrac{1}{3}f_{3m}\cos 3m\theta + \tfrac{1}{5}f_{5m}\cos 5m\theta - \ldots\Big\} \quad . \quad . \quad . \quad . \quad . \quad (39)$$

The series (38) and (39) for the M.M.F. distribution of a normal multipolar winding show the various terms with the actual corresponding numbers of pole-pairs, $m/2$, $3m/2$, $5m/2$, etc., and $m$, $3m$, $5m$, etc.

For certain purposes, such as when dealing with pole-changing windings, it is convenient to have the series in this form.

When dealing solely with the case of a normal winding it is naturally more convenient to express the series in terms of the main number of poles as the fundamental harmonic, and to have the angles expressed in terms of the electrical measure corresponding to the fundamental harmonic.

The series then become, respectively :—

$$x = \frac{4X}{\pi}\Big\{f_1'\sin a_1\cos\theta_1 + \tfrac{1}{3}f_3'\sin 3a_1\cos 3\theta_1 + \ldots\Big\}$$

for a winding with one coil per pole, and

$$x = \frac{2X}{\pi}\Big\{f_1'\cos\theta_1 - \tfrac{1}{3}f_3'\cos 3\theta_1 + \ldots\Big\}$$

for a hemitropic winding.

The factors $f_1'$, $f_3'$, etc., for the various harmonics are obtained readily from Figs. 7 and 9, or from Figs. 11 and 12. These graphs represent the values of the winding factor and the slot-width factor, plotted against the value of the slot-pitch and the slot width, respectively, expressed in electrical degrees to correspond to the particular order of harmonic under investigation. Figs. 11 and 12 are drawn to a scale suited for giving accurately the values for the fundamental harmonic, and Figs. 7 and 9 are especially suited for use in the case of the higher harmonics. The graphs are, of course, equally suited for use in ordinary calculations for the E.M.F. induced in armature windings, the winding factors for slotted armatures being readily obtained from Figs. 9 and 12, which are in a form particularly suited for use in a design office.

*Normal full-pitch windings.*—It is usual, in dealing with windings, to define the pitch as that measured from centre to centre of the phase bands, as in Fig. 17, and thus not necessarily as the mean span of the component coils.

In the case of a hemitropic winding of the concentric type the pitch has the same value as the mean span of the coil, and, if even harmonics in the M.M.F. wave are to be avoided, this mean span must be made equal to one pole-pitch. The use of any other span would result in the disturbance of the magnetic balance of any machine having an odd number of pole-pairs, and no instance of any normal hemitropic winding in which the mean span is not an exact pole-pitch has come to the author's notice.*

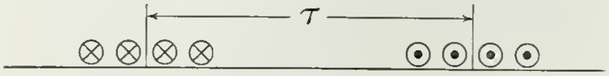
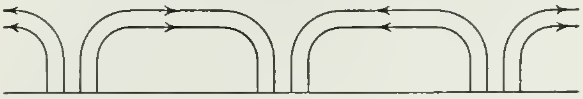
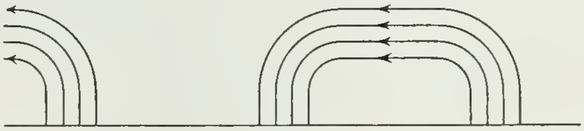


FIG. 17.

In a concentric winding having one coil per pole per phase, a full-pitch winding is obtained when the coils belonging to each phase are arranged as in Fig. 18 (*a*). The mean span of the component coils is thus $2a = \pi - 2s\gamma$, where $s$ is the number of slots per coil-side, i.e. $2s$ is the number of slots per phase band.



(*a*)



(*b*)

FIG. 18.

In the case of a two-phase winding, the mean span of the component coils is thus $2a = 3\pi/4$, and in the case of a three-phase winding $2a = 5\pi/6$. For a normal two-thirds winding the mean span of a single-phase winding is $2a = 2\pi/3$.

In dealing with such windings it is convenient to calculate on the basis of the equivalent hemitropic full-pitch winding [see Fig. 18 (*b*)]. That such a method is justifiable follows at once from first principles. It may also be shown mathematically as follows :—

$$x_p = \frac{4X}{\pi} \times \frac{1}{p} \times f_{sp} \times f_{wp} \sin p\alpha \qquad \text{[from (38)]}$$

$$= \frac{4X}{\pi} \times \frac{1}{p} \times f_{sp} \times \frac{\sin sp\gamma}{s \sin p\gamma} \times \sin p\left(\frac{\pi}{2} - s\gamma\right)$$

$$= \frac{4X}{\pi} \times \frac{1}{p} \times f_{sp} \times \sin p\frac{\pi}{2} \times \frac{\sin 2sp\gamma}{2s \sin p\gamma}$$

So far as the production of the main air-gap field is concerned, the winding shown in Fig. 18 (*a*) is therefore equivalent to that shown in Fig. 18 (*b*). (The effect of the "free" portions of the conductors is different with the hemitropic winding from that with the equivalent winding having one coil per pole.)

With two-layer windings, which are generally of the lattice or barrel type, the individual slot-coils of which the winding is built up all have the same span, which for a full-pitch winding must itself be an exact pole-pitch.

*Fractional-pitch windings.*—It has been seen that by choosing suitably the value of the mean span of the coil group, any particular harmonic can be eliminated from the resulting M.M.F. distribution wave. In consequence, by suitably choosing the value of the span $2a$ any particular harmonic can be eliminated from the E.M.F. induced in the winding by a rotating-field system. So that, in practice, fractional-pitch, or chorded, windings are sometimes used to obtain a pure E.M.F. wave. In addition there are certain electrical and mechanical advantages to be derived from the use of such windings in machines of large pole-pitch, such as turbo-alternators. With commutator machines, and in particular with rotary converters, chording the winding by one slot-pitch results in improved commutation conditions.

To avoid even harmonics in the M.M.F. wave, it is imperative that fractional-pitch windings should not be of the hemitropic type. Occasionally single-layer windings with one coil per phase per pole are used, but more often they are of the two-layer lattice type.*

## VI. THE RESULTING MAGNETOMOTIVE FORCE DISTRIBUTION DUE TO A SINGLE COIL CARRYING ALTERNATING CURRENT.

It is proposed to concentrate attention first upon the case of sinusoidal currents of the same frequency. Later, the effects of non-sinusoidal currents will be discussed.

Let $X_{max.}$ = the maximum value of the M.M.F. developed by the coil, and let $X_{max.} \cos \omega t$ = the value of the M.M.F. developed by the coil at any time $t$. Then the value of the difference of magnetic potential between stator and rotor at a point P displaced by $\theta$ radians from the axis of the coil, and at time $t$, is, from (3) :—

$$x = \frac{2}{\pi} X_{max.} \cos \omega t \Big\{ f_1 \sin \alpha \cos \theta + \tfrac{1}{2} f_2 \sin 2\alpha \cos 2\theta$$
$$+ \tfrac{1}{3} f_3 \sin 3\alpha \cos 3\theta + \ldots \Big\} \quad . \quad (40)$$

The general term is thus :—

$$x_p = \frac{2}{\pi} X_{max.} \cos \omega t \times \frac{1}{p} \times f_p \sin p\alpha \cos p\theta$$
$$= 2C_p \cos \omega t \cos p\theta$$
$$= C_p \cos(\omega t - p\theta) + C_p \cos(\omega t + p\theta) \quad . \quad (41)$$

where $2C_p = \frac{2}{\pi} \times X_{max.} \times \frac{1}{p} \times f_p \sin p\alpha$
= the maximum value of the amplitude of the $2p$-pole M.M.F. component.

The M.M.F. component corresponding to $2p$ poles may thus be resolved into two parts. The maximum value of each of these parts is independent of the value of $\theta$, and hence of the position of the point under consideration, and is equal to $C_p$. In short, each component M.M.F. is equivalent to two M.M.F.'s of constant amplitude, $C_p$, of sinusoidal distribution, and rotating synchronously in opposite directions. The component rotating in a positive* direction is represented by $C_p \cos(\omega t - p\theta)$, and the inverse component by $C_p \cos(\omega t + p\theta)$.

---

* One special instance of a hemitropic winding of such a type occurs when, in order to suppress tooth ripples in the E.M.F. wave, extra, idle, slots are provided. Such windings are very rare and quite special, since with polyphase machines certain coils would span one slot more than others.

* As shown later, when the number of phases *of the winding* is even, hemitropic fractional-pitch windings may be used without the production of even harmonics.

The series for the M.M.F. wave due to a single coil may thus be expressed in the form :—

$$x = \Big[\Big\{C_1 \cos(\omega t - \theta) + C_2 \cos(\omega t - 2\theta) + C_3 \cos(\omega t - 3\theta) + \ldots\Big\} + \Big\{C_1 \cos(\omega t + \theta) + C_2 \cos(\omega t + 2\theta) + C_3 \cos(\omega t + 3\theta) + \ldots\Big\}\Big] \quad . \quad (42)$$

The first of the two component series for $x$ contains solely the terms corresponding to M.M.F.'s rotating in a positive direction at angular speeds of $\omega$, $\omega/2$, $\omega/3$, etc., radians per second, and, in general, $\omega/p$ radians per second. The second contains all the terms corresponding to negative direction of rotation.

It is important to realize that, although each component M.M.F. may be resolved into two oppositely rotating M.M.F.'s of constant amplitude and waveform, it is not correct to deal in a similar manner with the M.M.F. wave as a whole. The author has already illustrated this point graphically.† Mathematically, it follows from (42) that the distribution waves for both the normal and the inverse rotating components have not a constant wave-form. The positive rotating component, for example, is represented by the series :—

$$x_a = C_1 \cos(\omega t - \theta) + C_2 \cos(\omega t - 2\theta) + C_3 \cos(\omega t - 3\theta) + \ldots$$

The wave-form represented by this series is obviously dependent not only upon the values of the coefficients $C_1$, $C_2$, etc., but also upon the value of $t$. The actual wave-form at any instant, expressed in a series of sines and cosines, is given by :—

$$x_a = \cos\omega t\Big\{C_1 \cos\theta + C_2 \cos 2\theta + C_3 \cos 3\theta + \ldots\Big\} + \sin\omega t\Big\{C_1 \sin\theta + C_2 \sin 2\theta + C_3 \sin 3\theta + \ldots\Big\} (43)$$

In a similar manner the wave-form of the inverse rotating component may be obtained, and is represented by :—

$$x_b = \cos\omega t\Big\{C_1 \cos\theta + C_2 \cos 2\theta + C_3 \cos 3\theta + \ldots\Big\} - \sin\omega t\Big\{C_1 \sin\theta + C_2 \sin 2\theta + C_3 \sin 2\theta + \ldots\Big\} (44)$$

Series (43) and (44) indicate that each rotating component of the actual alternating M.M.F. wave may, in turn, be resolved into two purely alternating components. The main axes of these two alternating components are displaced by 90° in space, and, the time displacement between them being $\frac{1}{4}$ period, there is a certain similarity to the case of a two-phase winding. An important difference from the two-phase case exists, however, in that the two alternating components have different wave-shapes, the one being represented by

$$C_1 \cos\theta + C_2 \cos 2\theta + C_3 \cos 3\theta + \ldots$$

and the other by

$$\begin{aligned} & C_1 \sin\theta + C_2 \sin 2\theta + C_3 \sin 3\theta + \ldots \\ & \quad = C_1 \cos(\theta - \tfrac{1}{2}\pi) - C_2 \sin 2(\theta - \tfrac{1}{2}\pi) - C_3 \cos 3(\theta - \tfrac{1}{2}\pi) \\ & \qquad + C_4 \sin 4(\theta - \tfrac{1}{2}\pi) + C_5 \cos 5(\theta - \tfrac{1}{2}\pi) - \ldots \end{aligned}$$

The difference in the wave-shapes is thus due to the difference in the phase relationships of certain of the harmonics.*

The cosine terms in (43) and (44) each represent exactly one-half of the alternating M.M.F. due to the coil ; the joint effect of the sine terms in the two series is, of course, zero. As a simple example, the case of a coil having a mean span of $\pi$ radians and a uniformly distributed coil-side spreading over $\pi$ radians may be taken. (The coil would thus correspond to a surface-wound, fully-distributed single-phase winding.) The actual M.M.F. distribution due to this coil, when carrying alternating current, is a wave-shape of triangular form represented by :—

$$x = \frac{4X_{max.}}{\pi^2} \cos\omega t\Big\{\cos\theta + \tfrac{1}{9}\cos 3\theta + \tfrac{1}{25}\cos 5\theta + \ldots\Big\}$$

The M.M.F. corresponding to the component rotating positively is :—

$$x_a = \frac{2X_{max.}}{\pi^2}\Big[\cos\omega t\Big\{\cos\theta + \tfrac{1}{9}\cos 3\theta + \tfrac{1}{25}\cos 5\theta + \ldots\Big\} + \sin\omega t\Big\{\sin\theta + \tfrac{1}{9}\sin 3\theta + \tfrac{1}{25}\sin 5\theta + \ldots\Big\}\Big]$$

The two series contained in the above expression represent, respectively, wave-shapes which are identical so far as the Ist, 5th, 9th, etc., harmonics are concerned, but the other harmonics are of opposite sign in the two cases.

The wave-shapes of the normal rotating component of the alternating M.M.F. will thus change periodically between these two waves as limiting conditions. The amplitude of any particular harmonic remains constant, but its relative phase changes.

It is thus necessary, when dealing with alternating M.M.F. waves, that the well-known method of replacing an alternating field by two equal and constant fields rotating synchronously in opposite directions shall be applied separately to each harmonic of the M.M.F. wave, and *not* to the wave as a whole.

## VII. THE RESULTING MAGNETOMOTIVE FORCE DISTRIBUTION DUE TO A NUMBER OF SIMILAR COILS CARRYING ALTERNATING CURRENT.

Attention will be confined to the case when the currents in the various coils have the same virtual value.

*Case* I. *Two coils displaced by* $2\psi$, *carrying currents*

---

* Positive direction of rotation is taken as counter-clockwise.

† *Journal I.E.E.*, 1919, Supplt. to vol. 57, p. 79.

* The series for the rotating components of the alternating M.M.F. due to a single coil include, respectively, all the harmonics rotating in a positive direction for the normal component, and in a negative direction for the inverse component. With a two-phase winding, the fundamental, fifth, ninth, etc., harmonics of the rotating M.M.F. rotate in a positive direction, and the third, seventh, eleventh, etc., in a negative direction.

*displaced by* $2\phi$.—Let $X_{max.} \cos \omega t$ = the M.M.F. developed by coil I, and $X_{max.} \cos (\omega t - 2\phi)$ = the M.M.F. developed by coil II.

Further, let coil II be $2\psi$ radians in advance of coil I, as in Fig. 13.

Then the difference of magnetic potential between stator and rotor at a point P distant by $\theta$ mechanical radians from the axis of coil I, due to the sole action of coil I, is, from (42) :—

$$\begin{aligned} x' = \Big\{ & C_1 \cos (\omega t - \theta) + C_2 \cos (\omega t - 2\theta) \\ & + C_3 \cos (\omega t - 3\theta) + \ldots \Big\} \\ & + \Big\{ C_1 \cos (\omega t + \theta) + C_2 \cos (\omega t + 2\theta) \\ & \quad + C_3 \cos (\omega t + 3\theta) + \ldots \Big\} \end{aligned}$$

The displacement of the above point from the axis of coil II is $(\theta - 2\psi)$ radians. Hence the effect of this second coil is represented by the series :—

$$\begin{aligned} x'' &= \cos (\omega t - 2\phi) \Big\{ 2C_1 \cos (\theta - 2\psi) + 2C_2 \cos 2(\theta - 2\psi) \\ &\qquad + 2C_3 \cos 3(\theta - 2\psi) + \ldots \Big\} \\ &= \Big\{ C_1 \cos [\omega t - \theta - 2(\phi - \psi)] \\ &\qquad + C_2 \cos [\omega t - 2\theta - 2(\phi - 2\psi)] + \ldots \Big\} \\ &\qquad + \Big\{ C_1 \cos [\omega t + \theta - 2(\phi + \psi)] \\ &\qquad + C_2 \cos [\omega t + 2\theta - 2(\phi + 2\psi)] + \ldots \Big\} \end{aligned}$$

The total effect of the two coils is therefore given by :—

$$\begin{aligned} x &= x' + x'' \\ &= 2\Big[ \Big\{ C_1 \cos (\phi - \psi) \cos [\omega t - \theta - (\phi - \psi)] \\ &\quad + C_2 \cos (\phi - 2\psi) \cos [\omega t - 2\theta - (\phi - 2\psi)] + \ldots \Big\} \\ &\quad + \Big\{ C_1 \cos (\phi + \psi) \cos [\omega t + \theta - (\phi + \psi)] \\ &\quad + C_2 \cos (\phi + 2\psi) \cos [\omega t + 2\theta - (\phi + 2\psi)] + \ldots \Big\} \Big] \qquad (45) \end{aligned}$$

The general term, corresponding to the $2p$-pole component of the resulting M.M.F. wave, is :—

$$\begin{aligned} x_p = 2\Big\{ & C_p \cos (\phi - p\psi) \cos [\omega t - p\theta - (\phi - p\psi)] \\ & + C_p \cos (\phi + p\psi) \cos [\omega t + p\theta - (\phi + p\psi)] \Big\} \qquad (46) \end{aligned}$$

Hence, so far as the $2p$-pole component of the resulting M.M.F. is concerned, the combined effect of the two coils is equivalent to the joint action of a constant $2p$-pole M.M.F. of sinusoidal distribution and amplitude $2C_p \cos (\phi - p\psi)$, rotating synchronously, i.e. at $2\omega/p$ radians per second, in a counter-clockwise direction, and a $2p$-pole M.M.F. of sinusoidal distribution and amplitude $2C_p \cos (\phi + p\psi)$ rotating synchronously in a clockwise direction.

The general term (46) may further be expanded by replacing $\cos (\phi - p\psi)$ by $\cos (\phi + p\psi) + 2 \sin \phi \sin p\psi$, and then is :—

$$\begin{aligned} x_p &= 2\Big[ C_p \Big\{ \cos (\phi + p\psi) \\ &\qquad + 2 \sin \phi \sin p\psi \Big\} \cos [\omega t - p\theta - (\phi - p\psi)] \\ &\qquad + C_p \cos (\phi + p\psi) \cos [\omega t + p\theta - (\phi + p\psi)] \Big] \\ &= 2\Big\{ 2C_p \cos (\phi + p\psi) \cos p(\theta - \psi) \cos (\omega t - \phi) \\ &\qquad + 2C_p \sin \phi \sin p\psi \cos [\omega t - p\theta - (\phi - p\psi)] \Big\} \qquad (47) \end{aligned}$$

Of these two terms, the former represents a purely alternating M.M.F. corresponding to $2p$ poles, of sinusoidal distribution and amplitude $4C_p \cos (\phi + p\psi) = 2 \times (2X_{max.}/\pi) \times 1/p \times f_p \sin p\alpha \cos (\phi + p\psi)$. The second term represents a constant sinusoidal M.M.F. of the same number of poles rotating synchronously in a counter-clockwise direction, its amplitude being $4C_p \sin \phi \sin p\psi$.

In a similar manner, by substituting $\cos (\phi - p\psi) - 2 \sin \phi \sin p\psi$ for $\cos (\phi + p\psi)$ in (46), the general term may be expressed in the form :—

$$\begin{aligned} x_p = 2\Big\{ & 2C_p \cos (\phi - p\psi) \cos p(\theta - \psi) \cos (\omega t - \phi) \\ & - 2C_p \sin \phi \sin p\psi \cos [\omega t + p\theta - (\phi + p\psi)] \Big\} \qquad (48) \end{aligned}$$

The resulting $2p$-pole component may therefore also be regarded as being equivalent to a pure sinusoidal alternating M.M.F. wave of amplitude $4C_p \cos (\phi - p\psi)$, together with a constant sinusoidal M.M.F. wave of amplitude $-4C_p \sin \phi \sin p\psi$ rotating synchronously in a clockwise direction.

The resulting $2p$-pole component is thus a constant, synchronously rotating M.M.F. if either $\cos (\phi + p\psi) = 0$, or $\cos (\phi - p\psi) = 0$.

If $\cos (\phi + p\psi) = 0$, the resulting $2p$-pole component is of sinusoidal distribution and amplitude $2C_p \cos (\phi - p\psi) = 2X_{max.}/\pi \times 1/p \times f_p \sin p\alpha \cos (\phi - p\psi)$ and rotates synchronously in a counter-clockwise direction.

Similarly, if $\cos (\phi - p\psi) = 0$, the component has an amplitude $2C_p \cos (\phi + p\psi)$ and rotates synchronously in a clockwise direction.

On the other hand, the $2p$-pole component is purely alternating when $\sin \phi \sin p\psi = 0$. The amplitude of the component will then have a maximum value of $4C_p \cos (\phi \pm p\psi)$.

Alternatively, the condition for the component to be purely alternating may be stated in the form $\pm \cos (\phi - p\psi) = \cos (\phi + p\psi)$.

In the general case the component corresponding to any particular number of poles will be partly alternating and partly rotating; it will always be of sinusoidal distribution, and its amplitude will vary between the limiting values of $4C_p \cos \phi \cos p\psi$ and $4C_p \sin \phi \sin p\psi$. The effect is thus of the nature of an elliptical rotating M.M.F., the direction of rotation being counter-clockwise when $\cos (\phi - p\psi)$ is numerically greater than $\cos (\phi + p\psi)$, and vice versa.

Hence, with two similar coils displaced by $2\psi$ radians, and carrying currents displaced by $2\phi$: *The condition for the $2p$-pole M.M.F. component to be a constant rotating M.M.F. is :—*

(*a*) *For counter-clockwise rotation :—*

$$\phi + p\psi = (2M - 1)\frac{\pi}{2}$$

$$\psi = \frac{1}{p}\Big\{ (2M - 1)\frac{\pi}{2} - \phi \Big\}$$

(*b*) *For clockwise rotation :—*

$$p\psi - \phi = (2M - 1)\frac{\pi}{2}$$

$$\psi = \frac{1}{p}\Big\{ (2M - 1)\frac{\pi}{2} + \phi \Big\}$$

In both (*a*) and (*b*) neither $\phi$ nor $p\psi$ must be a multiple of $\pi/2$.

*Case 2. Any number, m, of similar coils having a constant mechanical phase displacement $2\psi$ between successive coils, the currents in successive coils being displaced by $2\phi$.*—Using the same notation as in the previous case, the value of the M.M.F. developed by the $m$th coil will be represented by

$$X_{max.} \cos \left\{\omega t - 2(m-1)\phi\right\}$$

and this coil will be $2(m-1)\psi$ radians in advance of coil I.

The general term in the series for the M.M.F. distribution due to the joint action of the $m$ coils is then :—

$$\begin{aligned} x_p &= 2C_p\Big\{\cos p\theta \cos \omega t + \cos p(\theta-2\psi) \cos (\omega t-2\phi) + \ldots \\ &\qquad + \cos p[\theta-2(m-1)\psi] \cos [\omega t-2(m-1)\phi]\Big\} \\ &= C_p\Big[\Big\{\cos (\omega t-p\theta) + \cos [\omega t-p\theta-2(\phi-p\psi)] + \ldots \\ &\qquad + \cos [\omega t-p\theta-2(m-1)(\phi-p\psi)]\Big\} \\ &\qquad + \Big\{\cos(\omega t+p\theta) + \cos [\omega t+p\theta-2(\phi+p\psi)] + \ldots \\ &\qquad + \cos [\omega t+p\theta-2(m-1)(\phi+p\psi)]\Big\}\Big] \\ &= C_p\left\{\frac{\sin m(\phi-p\psi)}{\sin (\phi-p\psi)} \cos [\omega t-p\theta-(m-1)(\phi-p\psi)]\right. \\ &\qquad \left. + \frac{\sin m(\phi+p\psi)}{\sin (\phi+p\psi)} \cos [\omega t+p\theta-(m-1)(\phi+p\psi)]\right\} \quad (49) \\ &= mC_p\Big\{F'_p \cos (\omega t - \phi' - p\theta') \\ &\qquad + F''_p \cos (\omega t - \phi' + p\theta')\Big\} \quad . \quad (50) \end{aligned}$$

In this last expression, $\phi' = (m-1)\phi$, i.e. one-half of the angle by which the current in the last coil lags behind that in coil I, and $\theta' = \theta - (m-1)\psi$ represents the displacement of any point from an origin midway between the axes of the two extreme coils.

The factors $F'_p$ and $F''_p$ represent, respectively,

$$\frac{\sin m(\phi - p\psi)}{m \sin (\phi - p\psi)} \quad \text{and} \quad \frac{\sin m(\phi + p\psi)}{m \sin (\phi + p\psi)}$$

and are of the nature of coil " distribution factors " or " winding factors " for $m$ coils having a displacement of $2(p\psi - \phi)$ and $2(\phi + p\psi)$ electrical radians, respectively, between successive coils. These factors can be read off at once from the graphs given in Figs. 9 and 12.

The total resulting M.M.F. distribution due to the $m$ coils is therefore represented by the series :—

$$\begin{aligned} x = m\Big[&\Big\{F'_1 C_1 \cos (\omega t - \phi' - \theta') \\ &+ F'_2 C_2 \cos (\omega t - \phi' - 2\theta') + \ldots\Big\} \\ &+ \Big\{F''_1 C_1 \cos (\omega t - \phi' + \theta') \\ &+ F''_2 C_2 \cos (\omega t - \phi' + 2\theta') + \ldots\Big\}\Big] \quad (51) \end{aligned}$$

It is thus a great convenience when dealing with the M.M.F. developed by a number of coils fed with alternating currents, to resolve each individual alternating component of the M.M.F. developed by each of the coils into its two constant, oppositely rotating components, and then to deal separately with all the components rotating clockwise and with those rotating counter-clockwise for each number of poles.

In the case under consideration, the phase displacement in electrical radians between the rotating components due to successive coils for the $2p$-pole M.M.F. is $(p\psi - \phi)$ for the counter-clockwise components, and $(\phi + p\psi)$ for the clockwise components, as indicated in Fig. 19. The resulting amplitudes of the rotating M.M.F.'s for any value of $p$ are thus readily obtained by an ordinary vector construction, or, more simply, by reference to the graphs mentioned above.

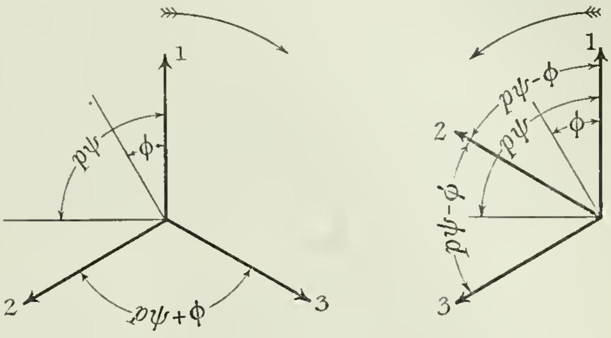


Fig. 19.

In general, the $2p$-pole component is of the nature of an elliptical rotating M.M.F. The direction of rotation is counter-clockwise when

$$\frac{\sin m(\phi - p\psi)}{\sin (\phi - p\psi)}$$

is numerically greater than

$$\frac{\sin m(\phi + p\psi)}{\sin (\phi + p\psi)}$$

and vice versa.

The distribution of the M.M.F. component is always sinusoidal, and the limiting values of its amplitude are, respectively, $mC_p(F'_p + F''_p)$ and $mC_p(F'_p - F''_p)$, i.e. $mX_{max.}/\pi \left\{f_p(1/p) \times \sin p\alpha(F'_p \pm F''_p)\right\}$.

The component is eliminated when both

$$\frac{\sin m(\phi - p\psi)}{\sin (\phi - p\psi)} \quad \text{and} \quad \frac{\sin m(\phi + p\psi)}{\sin (\phi + p\psi)} = 0$$

otherwise, when

$$\pm \frac{\sin m(\phi - p\psi)}{\sin (\phi - p\psi)} = \frac{\sin m(\phi + p\psi)}{\sin (\phi + p\psi)}$$

the component is purely alternating.

When $\sin m(\phi + p\psi)/\sin (\phi + p\psi) = 0$, the $2p$-pole component is a constant sinusoidal M.M.F. rotating synchronously in a counter-clockwise direction, and when $\sin m(\phi - p\psi)/\sin (\phi - p\psi) = 0$ the component rotates synchronously in a clockwise direction.

The following conclusions may thus be drawn for any particular component of the resulting M.M.F. wave :—

(1) The amplitude of the positively, i.e. counter-clockwise, rotating component has the maximum possible value of $mC_p$ when

$$\phi - p\psi = 0 \text{ or } M\pi\,^*$$

$$\text{i.e. when} \quad p = \frac{\phi}{\psi} \text{ or } \left(\frac{\phi}{\psi} - \frac{M\pi}{\psi}\right)$$

---

* $M$ is any integer, positive or negative.

(2) The amplitude of the negatively rotating component is equal to $mC_p$ when

$$\phi + p\psi = 0 \text{ or } M\pi$$

$$\text{i.e. when} \quad p = -\frac{\phi}{\psi} \text{ or } \left(\frac{M\pi}{\psi} - \frac{\phi}{\psi}\right)$$

(3) The positively rotating component is eliminated when

$$m(\phi - p\psi) = M\pi$$

$$p = \frac{\phi}{\psi} - \frac{M}{m} \times \frac{\pi}{\psi}$$

where $M/m$ is not an integer or zero.

(4) The negatively rotating component is eliminated when

$$m(\phi + p\psi) = M\pi$$

$$p = -\frac{\phi}{\psi} + \frac{M}{m} \times \frac{\pi}{\psi}$$

where $M/m$ is not an integer or zero.

(5) If both conditions (3) and (4) are fulfilled the $2p$-pole component is entirely eliminated.

(6) If condition (4) only is fulfilled, the component is a constant sinusoidal $2p$-pole M.M.F. rotating at synchronous speed in a positive direction, i.e. counter-clockwise.

(7) If condition (3) only is fulfilled, the component is a constant M.M.F. rotating synchronously in a negative direction.

(8) The component is purely alternating if $F_p' = \pm F_p''$, i.e. when

$$\frac{\sin m(\phi - p\psi)}{\sin (\phi - p\psi)} = \pm \frac{\sin m(\phi + p\psi)}{\sin (\phi + p\psi)}$$

*Case* 3. *Any number, m, of similar coils spaced uniformly around the armature, the currents in adjacent coils being displaced by* $2\phi$.—The resulting M.M.F. distribution may at once be deduced from (49) by substituting $2\pi/m$ for $2\psi$.

The general term in the resulting M.M.F. series thus becomes :—

$$x_p = C_p\left\{\frac{\sin (p\pi - m\phi)}{\sin (p\pi - m\phi)/m} \cos (\omega t - p\theta' - \phi') + \frac{\sin (p\pi + m\phi)}{\sin (p\pi + m\phi)/m} \cos (\omega t + p\theta' - \phi')\right\} \quad (52)$$

The positively and negatively rotating components, respectively, are therefore eliminated when $p = m\phi/\pi$ or $(m\phi/\pi) + Mm$, and when $p = Mm - (m\phi/\pi)$, where $M$ is any integer other than a multiple of $m$.

When $M$ *is* a multiple of $m$ in the above expressions the values of the rotating components have the maximum possible value of $mC_p$.

Since $p$ is of necessity an integer, for either of the above conditions to be satisfied it is necessary that $m\phi$ shall be a multiple of $\pi$.

The M.M.F. component is purely alternating when $\frac{\sin (p\pi - m\phi)}{\sin (p\pi - m\phi)/m} = \pm \frac{\sin (p\pi + m\phi)}{\sin (p\pi + m\phi)/m}$, i.e. when $p = Mm$, or $2\phi = 0$ or $\pi$.

So that, independent of the phase displacement $2\phi$ of the currents, when $p = Mm$, the $2p$-pole M.M.F. is purely alternating, and if $2\phi = 0$ or $\pi$, the resulting $2p$-pole component M.M.F. is purely alternating for all values of $p$.

Unless one of these two conditions is satisfied, the resulting M.M.F. corresponding to $2p$ poles will be of the nature of an elliptical rotating M.M.F. for all cases where $m\phi$ is *not* a multiple of $\pi$.

The case of $m\phi = M\pi$ is of considerable importance in practice: it is therefore considered separately.

*Case* 4. *Any number, m, of similar coils spaced uniformly around the armature, the phase displacement* $2\phi$ *between the currents in adjacent coils being a multiple of* $2\pi/m$.—Let $m\phi = q\pi$, where $q$ is any integer.

The general term corresponding to $2p$ poles now becomes, from (49) and (52) :—

$$x_p = C_p\left\{\frac{\sin (p-q)\pi}{\sin [(p-q)\pi]/m} \cos \left[\omega t - p\theta + (m-1)(p-q)\frac{\pi}{m}\right]\right.$$
$$\left.\frac{\sin (p+q)\pi}{\sin [(p+q)\pi]/m} \cos \left[\omega t + p\theta - (m-1)(p+q)\frac{\pi}{m}\right]\right\} \quad (53)$$

The rotating components are therefore eliminated for all cases where $\sin (p - q)\pi/m$, and $\sin (p + q)\pi/m$, respectively, are not zero.

Hence all the counter-clockwise rotating components are eliminated excepting those of the orders $q$ or $Mm + q$, and the only clockwise rotating components present are those of the orders $Mm - q$, where $M$ is any integer.

The two components for any given value of $p$ can only be equal when $(p - q)$ and $(p + q)$ are both multiples of $m$, or zero.

These conditions can only obtain when both $p$ and $q$ are odd multiples or both even multiples of $m/2$, so that the only values of $q$ that can fulfil these conditions are $q = 0$ and $q = m/2$, corresponding to $2\phi = 0$ or $\pi$.

In all cases the value of the amplitude of any component which is not eliminated will correspond to $mC_p$, and it may readily be shown that the terms corresponding to the rotating components that are not eliminated simplify to $mC_p \cos (\omega t - p\theta)$ and $mC_p \cos (\omega t + p\theta)$, respectively.

The resulting M.M.F. is therefore represented by the series :—

$$x = m\Big[\Big\{C_q \cos (\omega t - q\theta) + C_{m+q} \cos (\omega t - \overline{m+q}\theta) + \ldots\Big\}$$
$$+ \Big\{C_{m-q} \cos (\omega t + \overline{m - q}\theta)$$
$$+ C_{2m-q} \cos (\omega t + \overline{2m-q}\theta) + \ldots\Big\}\Big] \quad (54)$$

The deductions for the case under consideration may therefore be summed up as follows :—

(1) All M.M.F. components are eliminated, excepting those for which $(p - q)$ or $(p + q)$ is zero or a multiple of the number of coils.

(2) If $q = 0$, all components are eliminated for which the number of pole-pairs is not a multiple of the number of coils; in general both odd and even multiples may be present, and the resulting M.M.F. is purely alternating and does not rotate.

(3) If $q \doteq m/2$, i.e. $2\phi = \pi$, all components are eliminated for which the number of poles is not an odd multiple of the number of coils, and the resulting M.M.F. is again purely alternating, the maximum amplitude of each component present being $2mC_p$.

(4) If $p = q$ or $Mm + q$, the resulting $2p$-pole component is constant and rotates synchronously in a positive direction, its amplitude being $mC_p$.

(5) If $p = Mm - q$, the resulting $2p$-pole component is of constant amplitude $mC_p$, and rotates synchronously in a negative, i.e. clockwise, direction.

For (4) and (5), $q$ must not be zero or a multiple of $m/2$. The above statements hold good for all values of the coil-span and for the spread of the coil-side. These latter determine the value of $C_p$ but otherwise do not affect the problem.

To illustrate this particular case, Table 4 has been prepared for a stator wound with 12 coils, and for values of $q$ from 0 to 12, inclusive.

TABLE 4.

*The Orders of the M.M.F. Components established by a Winding with 12 Coils, uniformly spaced around the Armature, for Various Values of the Phase Displacement between the Currents in Adjacent Coils.*

| $q$ | $2\phi$ in degrees | Orders of M.M.F. components | | Remarks |
|---|---|---|---|---|
| | | Positive rotation | Negative rotation | |
| 1 | 30 | 1, 13, 25, 37, etc. | 11, 23, 35, etc. | 2-pole, 12-phase |
| 2 | 60 | 2, 14, 26, 38 ,, | 10, 22, 34 ,, | 4-pole, 6-phase |
| 3 | 90 | 3, 15, 27, 39 ,, | 9, 21, 33 ,, | 6-pole, 4-phase |
| 4 | 120 | 4, 16, 28, 40 ,, | 8, 20, 32 ,, | 8-pole, 3-phase |
| 5 | 150 | 5, 17, 29, 41 ,, | 7, 19, 31 ,, | — |
| 6 | 180 | 6, 18, 30, 42 ,, | 6, 18, 30 ,, | 12-pole, single-phase |
| 7 | 210 | 7, 19, 31, 43 ,, | 5, 17, 29 ,, | — |
| 8 | 240 | 8, 20, 32, 44 ,, | 4, 16, 28 ,, | 8-pole, 3-phase |
| 9 | 270 | 9, 21, 33, 45 ,, | 3, 15, 27 ,, | 6-pole, 4-phase |
| 10 | 300 | 10, 22, 34, 46 ,, | 2, 14, 26 ,, | 4-pole, 6-phase |
| 11 | 330 | 11, 23, 35, 47 ,, | 1, 13, 25 ,, | 2-pole, 12-phase |
| 12 (0) | 0 | 12, 24, 36, 48 ,, | 12, 24, 36 ,, | 24-pole, single-phase hemitropic |

For the latter half of the table the main direction of rotation of the resulting M.M.F. is negative, and for the former half, positive. It will be noted that even harmonics of the lowest order present only occur when $q = 4$ or 8.

## VIII. THE NORMAL POLYPHASE WINDING.

In dealing with polyphase windings a certain degree of complexity arises out of the fact that it has become the custom to designate the windings by the number of phases of the supply system. Thus all windings fed from a three-phase supply are usually called three-phase windings, and those from a two-phase supply, two-phase windings, so that a winding may have either one or two coils per pair of poles for each "phase." Further, there is the unfortunate fact that whereas with three-phase currents the displacement between the phases is $2\pi/3$, with so-called two-phase currents the displacement is not $2\pi/2$, but $2\pi/4$. In short, we have to deal with both symmetrical polyphase systems and hemi-symmetrical systems, the two-phase system representing simply two consecutive phases of a symmetrical four-phase system.

With a symmetrical system having an odd number of phases, the system can be regarded as forming one-half of a symmetrical system having double the number of phases of the supply, as shown in Fig. 20. For example, there is no difficulty in feeding a normal six-phase motor winding from a three-phase supply.

With a symmetrical system having an even number of phases, on the other hand, the supply cannot be utilized for feeding a winding having double the number of phases. For example, 12-phase currents cannot be supplied to a 12-phase motor winding direct from a six-phase supply.

A hemi-symmetrical polyphase system can naturally be used to feed a symmetrical winding having double the number of phases of the supply; e.g. a normal four-phase winding can be supplied from a two-phase supply.

It is inconvenient to have to deal separately with the various types of winding, and it is desirable to find some means of making all the types fall simply into one common category.

Now it may be taken that in every case of a normal polyphase winding the coils are uniformly spaced, and that if $N$ is the number of coils, i.e. coil groups, per pair of poles, the phase displacement between the currents in adjacent coils is $2\pi/N$.* The author therefore finds it a convenience to define the number of phases of the winding as being equal to the number of coil groups per pair of poles, i.e. equal to $N$. If the number of coils per pair of poles is odd, then the number of phases of the supply system must be equal to $N$. If, however, $N$ is an odd multiple of 2, then the number of phases of the supply system need only be $N/2$; in addition, with a hemi-symmetrical supply system, the number of phases of the supply will be $N/2$.

---

* Thus a motor fed from a three-phase supply may have three coils per main pair of poles, the phase displacement between the currents in neighbouring coils being $2\pi/3$, or it may have six coils per pair of poles, fed with currents displaced, in neighbouring coils, by $2\pi/6$. With a two-phase supply it is practically invariable to have four coils per pair of poles, and to feed them with currents displaced, in neighbouring coils, by $2\pi/4$.

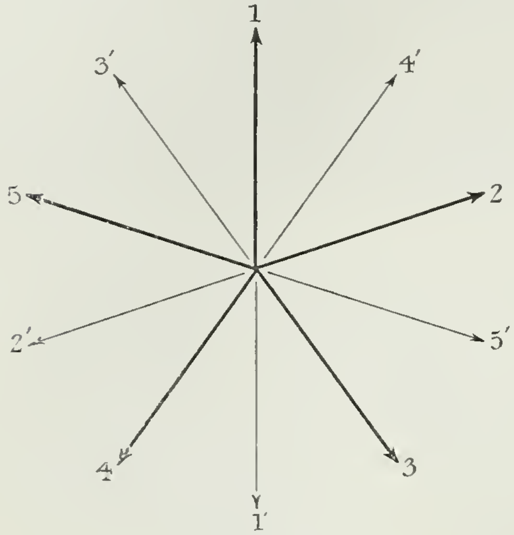


Fig. 20.

The Fourier series for the M.M.F. distribution of a normal polyphase winding follows at once from the previous section. The total number of coils, $m$, is now equal to $Nq$, since $q$ is the number of main pairs of poles.

The M.M.F. distribution is therefore obtained from (54) by substituting $Nq$ for $m$, and becomes:—

$$\begin{aligned}x &= m\Big\{[C_q\cos(\omega t-q\theta)+C_{m+q}\cos(\omega t-\overline{m+q}\theta)+\ldots]\\&\quad+[C_{m-q}\cos(\omega t+\overline{m-q}\theta)\\&\qquad+C_{2m-q}\cos(\omega t+\overline{2m-q}\theta)+\ldots]\Big\}\\&=Nq\Big\{[C_q\cos(\omega t-q\theta)+C_{(N+1)q}\cos(\omega t-(N+1)q\theta)+\ldots]\\&\quad+[C_{(N-1)q}\cos(\omega t+\overline{N-1}q\theta)\\&\qquad+C_{(2N-1)q}\cos(\omega t+\overline{2N-1}q\theta)+\ldots]\Big\}\\&=N\frac{X_{max.}}{\pi}\Bigg\{\Bigg[f_q\sin qa\cos(\omega t-q\theta)\\&\quad+\frac{1}{N+1}f_{q(N+1)}\sin(N+1)qa\cos(\omega t-\overline{N+1}q\theta)+\ldots\Bigg]\\&\quad+\Bigg[\frac{1}{N-1}f_{q(N-1)}\sin(N-1)qa\cos(\omega t+\overline{N-1}q\theta)+\ldots\Bigg]\Bigg\}\end{aligned}\tag{55}$$

Representing now the various angles in electrical measure, based upon $2q$ poles, the series becomes:—

$$\begin{aligned}x&=N\frac{X_{max.}}{\pi}\Bigg\{\Bigg[f_1'\sin a_1\cos(\omega t-\theta_1)\\&\quad+\frac{1}{N+1}f_{N+1}'\sin(N+1)a_1\cos(\omega t-\overline{N+1}\theta_1)+\ldots\Bigg]\\&\quad+\Bigg[\frac{1}{N-1}f_{N-1}'\sin N(-1)a_1\cos(\omega t+\overline{N-1}\theta_1)+\ldots\Bigg]\Bigg\}\end{aligned}\tag{56}$$

Under these conditions, therefore, the only harmonics present in the resulting M.M.F. wave are certain multiples of $q$, the main number of pole-pairs, and, quite independent of the span of the coil groups, the elimination of the higher harmonics becomes more and more complete as the number of phases of the winding is increased.

If $N$ is an even number, independent of the span of the coil groups, even harmonics, i.e. components corresponding to an even multiple of $2q$ poles, are entirely eliminated, since in that case $MN \pm 1$ must be an odd number.

If, however, $N$ is an odd number, even harmonics may be present unless the span is suitably chosen, since $(2M-1)N \pm 1$ will be an even number. It therefore becomes necessary to employ full-pitch windings in such cases, so that $\sin qa = 1\cdot 0$.

For a full-pitch winding,* when $N$ is an odd number the series becomes:—

$$\begin{aligned}x&=\frac{NX_{max.}}{\pi}\Bigg[\Bigg\{f_1'\cos(\omega t-\theta_1)\\&\qquad-\frac{1}{2N+1}f_{2N+1}'\cos(\omega t-\overline{2N+1}\theta_1)+\ldots-\ldots\Bigg\}\\&\quad+\Bigg\{\frac{1}{2N-1}f_{2N-1}'\cos(\omega t+\overline{2N-1}\theta_1)\\&\qquad-\frac{1}{4N-1}f_{4N-1}\cos(\omega t+\overline{4N-1}\theta_1)+\ldots-\ldots\Bigg\}\Bigg]\end{aligned}$$

Similarly, when $N$ is an odd multiple of 2 the series for the M.M.F. developed by a winding in which the coils have a mean span of an exact pole-pitch is:—

$$\begin{aligned}x&=\frac{NX_{max.}}{\pi}\Bigg[\Bigg\{f_1'\cos(\omega t-\theta_1)\\&\qquad-\frac{1}{N+1}f_{N+1}'\cos(\omega t-\overline{N+1}\theta_1)+\ldots-\ldots\Bigg\}\\&\quad+\Bigg\{\frac{1}{N-1}f_{N-1}'\cos(\omega t+\overline{N-1}\theta_1)\\&\qquad-\frac{1}{2N-1}f_{2N-1}'\cos(\omega t+\overline{2N-1}\theta_1)+\ldots-\ldots\Bigg\}\Bigg]\end{aligned}$$

and when the value of $N$ is an even multiple of 2 the series becomes:—

$$\begin{aligned}x&=\frac{NX_{max.}}{\pi}\Bigg[\Bigg\{f_1'\cos(\omega t-\theta_1)\\&\qquad+\frac{1}{N+1}f_{N+1}'\cos(\omega t-\overline{N+1}\theta_1)+\ldots-\ldots\Bigg\}\\&\quad-\Bigg\{\frac{1}{N-1}f_{N-1}'\cos(\omega t+\overline{N-1}\theta_1)\\&\qquad+\frac{1}{2N-1}f_{2N-1}'\cos(\omega t+\overline{2N-1}\theta_1)+\ldots-\ldots\Bigg\}\Bigg]\end{aligned}$$

For the case of full-pitch coils, therefore, it is thus an advantage to have an odd number of coils per pair of poles, so far as the production of a pure rotating M.M.F. is concerned.

Thus, for example, with a 9-phase winding the lowest orders of higher harmonics present are the 17th and

---

* This involves the value of the mean span of the coil being an exact pole-pitch.

19th, as compared with the 11th and 13th present with a 12-phase winding.

On the other hand it must be remembered that chording the winding has important advantages, and that, by adopting a suitable span for the coil when $N$ is even, the importance of any of the high harmonics present may be very considerably reduced.

The orders of the harmonics present for various values of the number of coils per pair of poles, i.e. the number of phases of the winding, and for full-pitch coils, are given in tabular form above.

*Harmonics present in the Resulting M.M.F. of Polyphase Windings.*

| Number of phases, i.e. number of coils per pair of poles $N =$ | Order of harmonic | |
|---|---|---|
| | Positive rotation | Negative rotation |
| 3 | 1, 7, 13, 19, 25, 31, etc. | 5, 11, 17, 23, 29, etc. |
| 4 | 1, 5, 9, 13, 17, 21, etc. | 3, 7, 11, 15, 19, etc. |
| 6 | 1, 7, 13, 19, 25, 31, etc. | 5, 11, 17, 23, 29, etc. |
| 8 | 1, 9, 17, 25, 33, 41, etc. | 7, 15, 23, 31, 39, etc. |
| 9 | 1, 19, 37, 55, etc. | 17, 35, 53, etc. |
| 12 | 1, 13, 25, 37, etc. | 11, 23, 35, etc. |

For both $N = 3$ and $N = 6$, the only odd harmonics that are eliminated by the interaction of the phases of the winding are those of the third order, viz. the 3rd, 9th, 15th, etc.

For $N = 4$, the interaction of the phases does not result in the elimination of any of the higher harmonics of odd orders.

As a result, the fluctuations in the armature M.M.F. of machines with $N = 4$ (a number commonly employed with two-phase machines) may be of considerable importance, even in the case of alternating-current generators and synchronous motors.*

With $N = 3$ or $N = 6$ (numbers commonly employed for three-phase machines) the fluctuations in the armature M.M.F. are rarely of importance in the case of alternators or synchronous motors, but become very important in the case of synchronous converters.†

With $N = 9$, the elimination of the higher harmonics is very perfect, the 5th, 7th, 11th and 13th present in the case of $N = 3$ or $N = 6$, being absent.

The theory of the M.M.F. developed by the various types of two-phase and three-phase windings has been ably given by Mr. B. Hague,‡ so that it is not proposed to deal in great detail with the subject in the present paper, but to concentrate attention upon such matters as may throw additional light upon the subject.

*Uniformly distributed windings.*—It is proposed to deal first with windings of the two-layer type.

It may be taken that the average effect of the magnetomotive force established by a winding in which the slots are "skewed" corresponds sufficiently closely to that of a uniformly distributed winding. The case under consideration may therefore be taken as applying directly to a synchronous converter in which the slots are skewed.

The spread, $2\beta_1$, of each of the phase groups is, in electrical measure, $2\beta_1 = 2\pi/N$, i.e. $\beta_1 = \pi/N$.

The distribution factors for the various harmonics which may be present in the resulting M.M.F. thus become :—

$$f'_1 = \frac{\sin\beta_1}{\beta_1} \qquad = \frac{\sin(\pi/N)}{\pi/N}$$

$$f'_{[(2M-1)N+1]} = \frac{\sin[(2M-1)N+1]\frac{\pi}{N}}{[(2M-1)N+1]\frac{\pi}{N}} = -\frac{1}{(2M-1)N+1} \times f'_1$$

$$f'_{[(2M-1)N-1]} = \frac{\sin[(2M-1)N-1]\frac{\pi}{N}}{[(2M-1)N-1]\frac{\pi}{N}} = \frac{1}{(2M-1)N-1} \times f'_1$$

$$f'_{2MN+1} = \frac{1}{2MN+1} f'_1$$

$$f'_{2MN-1} = -\frac{1}{2MN-1} f'_1$$

The series for the resulting M.M.F. for an $N$-phase winding with full-pitch coils, at a point P distant by $\theta_1$ electrical radians from the axis of one of the coils, is thus :—

(*a*) when $N$ is an odd number,

$$x = \frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg\{\Bigg[\cos(\omega t - \theta_1) - \frac{1}{(2N+1)^2}\cos(\omega t - \overline{2N+1}\theta_1) + \ldots - \ldots\Bigg] + \Bigg[-\frac{1}{(2N-1)^2}\cos(\omega t + \overline{2N-1}\theta_1) + \frac{1}{(4N-1)^2}\cos(\omega t + \overline{4N-1}\theta_1) - \ldots\Bigg]\Bigg\} \quad (57)$$

---

* See, for instance, A. E. CLAYTON : "The Wave-shapes obtaining with Alternating-current Generators working under Steady Short-circuit Conditions," *Journal I.E.E.*, 1916, vol. 54, p. 92.

† See, for instance, MILES WALKER : "The Diagnosis and Cure of Troubles in Electrical Machinery," pp. 357 and 358.

‡ B. HAGUE : "The Mathematical Treatment of the Magnetomotive Force of Armature Windings," *Journal I.E.E.*, 1917, vol. 55, p. 489.

(*b*) when $N$ is an odd multiple of 2,

$$x = \frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg[\Bigg\{\cos(\omega t - \theta_1) + \frac{1}{(N+1)^2}\cos(\omega t - \overline{N+1}\theta_1) + \dots\Bigg\} + \Bigg\{\frac{1}{(N-1)^2}\cos(\omega t + \overline{N-1}\theta_1) + \frac{1}{(2N-1)^2}\cos(\omega t + 2\overline{N-1}\theta_1) + \dots\Bigg\}\Bigg] \quad (58)$$

and (*c*) when $N$ is an even multiple of 2,

$$x = \frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg[\Bigg\{\cos(\omega t - \theta_1) - \frac{1}{(N+1)^2}\cos(\omega t - \overline{N+1}\theta_1) + \dots - \dots\Bigg\} + \Bigg\{-\frac{1}{(N-1)^2}\cos(\omega t + \overline{N-1}\theta_1) + \frac{1}{(2N-1)^2}\cos(\omega t + 2\overline{N-1}\theta_1) - \dots + \dots\Bigg\}\Bigg] \quad (59)$$

The series given in (*b*) and (*c*) represent exactly the same wave-form, with the exception of a phase displacement of $\pi/2N$. By changing the origin, as in Fig. 21, to a point between successive phase bands, the resulting M.M.F. may, in every case when $N$ is even, be represented by :—

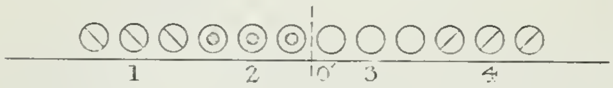


FIG. 21.

$$x = \frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg[\cos(\omega t - \theta_1) + \Bigg\{\frac{1}{(N+1)^2}\cos(\omega t - \overline{N+1}\theta_1) + \frac{1}{(N-1)^2}\cos(\omega t + \overline{N-1}\theta_1)\Bigg\} + \dots\Bigg] \quad (60)$$

and when $N$ is odd by :—

$$x = \frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg[\cos(\omega t - \theta_1) + \Bigg\{\frac{1}{(2N+1)^2}\cos(\omega t - \overline{2N+1}\theta_1) + \frac{1}{(2N-1)^2}\cos(\omega t + \overline{2N-1}\theta_1)\Bigg\} + \dots\Bigg] \quad (61)$$

These series will hold when the M.M.F. developed by the coil *after* the origin is represented by $X_{max.}\sin\omega t$ when $N$ is an even multiple of 2, and by

$X_{max.}\sin[\omega t + (\pi/N)]$ and $X_{max.}\sin[\omega t + (2\pi)/N]$

in the other cases, respectively.

The resulting M.M.F. distribution will thus vary periodically between two limiting forms represented respectively, when $N$ is even, by :—

$$\frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg\{\cos\theta_1 + \Bigg[\Bigg\{\frac{1}{(N-1)^2}\cos(N-1)\theta_1 + \frac{1}{(N+1)^2}\cos(N+1)\theta_1\Bigg\} + \dots\Bigg]\Bigg\} \quad . \quad (62)$$

and

$$\frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg\{\cos\theta_1 - \Bigg[\frac{1}{(N-1)^2}\cos(N-1)\theta_1 + \frac{1}{(N+1)^2}\cos(N+1)\theta_1\Bigg] + \Bigg[\frac{1}{(2N-1)^2}\cos(2N-1)\theta_1 + \frac{1}{(2N+1)^2}\cos(2N+1)\theta_1\Bigg] - \dots + \dots\Bigg\} \quad (63)$$

The first of these wave-forms obtains when the axis of the resulting M.M.F. coincides with the junction of two successive phases, and the second when the axis of the M.M.F. is at the centre of a phase band.

It may readily be shown that, to a very close approximation, the maximum value of the amplitude of the resulting M.M.F. due to a polyphase winding as given above reduces to *

$$\frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg\{1 + \frac{\pi^2}{3N^2}\Bigg(1 + \frac{3}{N^2}\Bigg)\Bigg\} \quad (64)$$

and the minimum value to

$$\frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg\{1 - \frac{\pi^2}{6N^2}\Bigg(1 + \frac{3}{N^2}\Bigg)\Bigg\} \quad (65)$$

The total fluctuation in the value of the amplitude of the resulting M.M.F. is thus :—

$$\frac{NX_{max.}}{\pi} \times \frac{\sin(\pi/N)}{\pi/N}\Bigg\{\frac{\pi^2}{2N^2}\Bigg(1 + \frac{3}{N^2}\Bigg)\Bigg\}$$

Expressed as a fraction of the fundamental harmonic, the total fluctuation in the value of the amplitude is therefore :—

$$\frac{\pi^2}{2N^2}\Bigg(1 + \frac{3}{N^2}\Bigg)$$

*The deviation from the value of the fundamental thus varies inversely as the square of the number of phases of the winding* (attention is, at the moment, confined to the case of an even number of phases).

---

* To a first approximation, the series inside the square brackets in (62), when $\theta_1 = 0$, reduces to

$$\frac{2}{N^2}\Bigg\{1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \dots\Bigg\}$$

the sum of which is $\pi^2/3N^2$.

By taking the formula given in (64), a closer approximation is obtained.

*Note* :—

$$\frac{1}{(N-1)^2} + \frac{1}{(N+1)^2} = 2(N^{-2} + 3N^{-4} + \dots)$$

When the number of phases is odd, the limiting values of the amplitude of the resulting M.M.F. are respectively:—

$$\frac{NX_{max.}}{\pi}\times\frac{\sin(\pi/N)}{\pi/N}\left\{1+\frac{1}{(2N-1)^2}+\frac{1}{(2N+1)^2}+\ldots\right\}$$

$$\doteqdot\frac{NX_{max.}}{\pi}\times\frac{\sin(\pi/N)}{\pi/N}\left\{1+\frac{\pi^2}{12N^2}\left(1+\frac{3}{4N^2}\right)\right\}\quad(66)$$

and

$$\frac{NX_{max.}}{\pi}\times\frac{\sin(\pi/N)}{\pi/N}\left\{1-\left(\frac{1}{(2N-1)^2}+\frac{1}{(2N+1)^2}\right)\right.$$

$$\left.+\left(\frac{1}{(4N-1)^2}\right)+\left(\frac{1}{(4N+1)^2}\right)+\ldots\right\}$$

$$\doteqdot\frac{NX_{max.}}{\pi}\times\frac{\sin(\pi/N)}{\pi/N}\left\{1-\frac{\pi^2}{24N^2}\left(1+\frac{3}{4N^2}\right)\right\}\quad(67)$$

So far as the M.M.F. wave is concerned, the percentage deviation from the fundamental harmonic, when $N$ is odd, is thus the same as for a number of phases equal to $2N$.

For all practical purposes, the values deduced from formulæ (64) to (67) are sufficiently exact, with the possible exception of cases in which extreme accuracy is required in dealing with a winding in which $N = 4$. Even with this low value of $N$, the values deduced for the amplitudes have an error of only 0·8 per cent for the maximum amplitude, and 0·5 per cent for the minimum. For $N = 3$ or $N = 6$, the corresponding errors are only about 0·25 per cent and 0·15 per cent, the error decreasing very rapidly as the number of phases increases.

It is a convenience to have the various values of the M.M.F. expressed in terms of the total number of ampere-conductors per pole on the armature. If $Z_a$ is the total number of conductors on the armature, $I_a\sqrt{2}$ the maximum value of the current per conductor, and $p_m$ the number of main pairs of poles:—

$$X_{max.}=\frac{I_aZ_a}{2p_mN}\times\sqrt{2}$$

and the amplitude of the fundamental becomes

$$\frac{NX_{max.}}{\pi}\times\frac{\sin(\pi/N)}{\pi/N}=\frac{I_aZ_a}{2p_m}\times\frac{\sqrt{2}}{\pi}\times\frac{\sin(\pi/N)}{\pi/N}$$

$$=\frac{I_aZ_a}{2p_m}\times\frac{\sqrt{2}}{\pi}f_1'$$

$$=0\cdot450\,f_1'\,\frac{I_aZ_a}{2p_m}$$

The limiting values of the M.M.F. are therefore given by

$$0\cdot450\,f_1'\,\frac{I_aZ_a}{2p_m}\left\{1+\frac{\pi^2}{3N^2}\left(1+\frac{3}{N^2}\right)\right\}$$

and $0\cdot450f_1'\times\frac{I_aZ_a}{2p_m}\left\{1-\frac{\pi^2}{6N^2}\left(1+\frac{3}{N^2}\right)\right\}$ when $N$ is even,

and $0\cdot450f_1'\times\frac{I_aZ_a}{2p_m}\left\{1+\frac{\pi^2}{12N^2}\left(1+\frac{3}{4N^2}\right)\right\}$

and $0\cdot450f_1'\times\frac{I_aZ_a}{2p_m}\left\{1-\frac{\pi^2}{24N^2}\left(1+\frac{3}{4N^2}\right)\right\}$ when $N$ is odd.

It will be noticed that for all practical purposes the difference between the maximum value of the amplitude and the amplitude of the fundamental harmonic is twice as great as the difference between the amplitude of the fundamental and the minimum amplitude of the resulting M.M.F.

Table 5 gives the values of the various amplitudes for different values of the number of phases. The values are given in terms of the value of the "virtual" ampere-conductors per pair of poles, and also as a percentage of the fundamental harmonic.

TABLE 5.

*The Amplitude of the Resulting Magnetomotive Force of Polyphase Windings.*

(The table refers to the case of full-pitch two-layer windings. $N$ denotes the number of phases of the winding, i.e. the number of complete coils per pair of poles.)

| Number of phases $N =$ | Value of amplitude of M.M.F. | | | | | |
|---|---|---|---|---|---|---|
| | Actual value $[(I_aZ_a)/(2p_m)]\times$ | | | Relative value | | |
| | Fundamental | Maximum value | Minimum value | Fundamental | Maximum value | Minimum value |
| 3 | 0·372 | 0·408 | 0·354 | 1·000 | 1·096 | 0·950 |
| 4 | 0·405 | 0·495 | 0·353 | 1·000 | 1·221 | 0·872 |
| 6 | 0·430 | 0·471 | 0·408 | 1·000 | 1·096 | 0·950 |
| 8 | 0·439 | 0·463 | 0·428 | 1·000 | 1·054 | 0·976 |
| 9 | 0·441 | 0·446 | 0·439 | 1·000 | 1·010 | 0·995 |
| 12 | 0·445 | 0·455 | 0·440 | 1·000 | 1·023 | 0·988 |
| 15 | 0·447 | 0·449 | 0·446 | 1·000 | 1·004 | 0·998 |
| 18 | 0·448 | 0·453 | 0·446 | 1·000 | 1·010 | 0·995 |

(*Note.*—The figures given above are for uniformly distributed windings and may be taken to correspond sufficiently exactly to the case of a machine with skewed slots.)

*The magnetomotive-force ripples.*—Series (57) shows that the resulting M.M.F. of a uniformly distributed polyphase winding is equivalent to a constant fundamental harmonic rotating in a positive direction at synchronous speed, and to a number of ripples represented by the joint action of harmonics of orders $MN + 1$, and $MN - 1$ rotating at $1/(MN + 1)$th and $1/(MN - 1)$th of the speed of the fundamental, in positive and negative directions respectively.

For even values of $N$, $M$ is any integer, but for odd values of $N$, $M$ must be an even integer.

The combined effect of the $(MN + 1)$th and the $(MN - 1)$th harmonics is thus of interest.

To a first approximation, unless $MN$ is relatively small, the joint effect of the pair of harmonics may be represented by:—

$$\frac{NX_{max.}}{\pi} f_1' \left\{ \frac{1}{(MN-1)^2} \cos(\omega t + \overline{MN-1}\theta_1) \right.$$

$$\left. + \frac{1}{(MN+1)^2} \cos(\omega t - \overline{MN+1}\theta_1) \right\}$$

$$\doteqdot \frac{NX_{max.}}{\pi} f_1' \left\{ \frac{1}{M^2N^2} [\cos(\omega t - \overline{MN+1}\theta_1) \right.$$

$$\left. + \cos(\omega t + \overline{MN-1}\theta_1)] \right\}$$

$$\doteqdot \frac{NX_{max.}}{\pi} \times \frac{f'}{M^2N^2} \left\{ 2\cos(\omega t - \theta_1) \cos MN\theta_1 \right\}$$

The term $\cos(\omega t - \theta_1)$ indicates that the disturbance corresponding to the combined effect of the two harmonics travels at synchronous speed, and the term $\cos MN\theta_1$ indicates that nodes always occur at points where $\cos MN\theta_1 = 0$, i.e. at the points on the armature where $\theta_1 = \pi/2MN$, $3\pi/2MN$, $5\pi/2MN$, etc. As a result, the wave-shape representing the ripple due to the $(MN \pm 1)$th harmonics corresponds somewhat to the tooth ripple due to flux-swinging in the pressure-wave of a machine having $MN$ slots per pair of poles, but the wave-shape of the complete ripple varies periodically. The half-period of the cycle of changes corresponds to a motion of the fundamental component corresponding to $\pi/MN$ electrical radians, and hence the frequency of the changes is $MN$ times the main frequency of the alternating currents in the winding. The ripple thus swings relatively to the main M.M.F. component as indicated in Fig. 22, which is drawn for the case when $MN = 6$.

The series for the total resulting M.M.F. due to a uniformly distributed polyphase winding may therefore be approximately represented by:—

$$x \doteqdot \frac{NX_{max.}}{\pi} f_1' \cos(\omega t - \theta_1) \left\{ 1 + \frac{2}{N^2} (\cos N\theta_1 \right.$$

$$\left. + \tfrac{1}{4} \cos 2N\theta_1 + \tfrac{1}{9} \cos 3N\theta_1 + \ldots) \right\}^* \quad . \quad (68)$$

The wave-shape of the resulting M.M.F. may thus be resolved into a constant fundamental together with a series of ripple disturbances as in Fig. 22, corresponding to $N$, $2N$, $3N$, etc., ripples per period. (When $N$ is odd, the ripples correspond only to the even multiples of $N$.) Each of these ripples gives rise to an effect corresponding to flux-swinging, the frequency of the swing being respectively $N$, $2N$, $3N$, etc., times the frequency of the alternating currents, and the effect is a maximum at the axis of the resulting M.M.F. of the complete winding.

In the case of rotating-armature machines, such as, in particular, synchronous converters, the axis of the resulting fundamental harmonic of the armature M.M.F. is stationary in space, so that the effect of the variations in the armature M.M.F. actually corresponds to the flux swinging backwards and forwards in space, and the magnetic oscillations so established may be of considerable importance. In the case of synchronous converters working at any normal power factor the magnetic oscillations will be very marked and, in most cases, practically maximum in the neighbourhood of the interpoles.

For low values of $MN$ the ripple shown in Fig. 22 and series (68) do not represent fully the M.M.F. corresponding to the harmonics of the orders $MN \pm 1$, but in every case represent by far the major portion of the effects due to these harmonics.

*The general case of a winding in slots.*—As already stated, the case of a winding in skewed slots may be considered to be sufficiently covered by that just considered. For other cases it is, in general, necessary to make use of the expression given in (56). The only higher harmonics present are, for the greater part, of sufficiently high orders to make the assumption that the M.M.F. of each slot is concentrated at its centre line unwarrantable, and to make it imperative to take the slot-width factor into consideration.

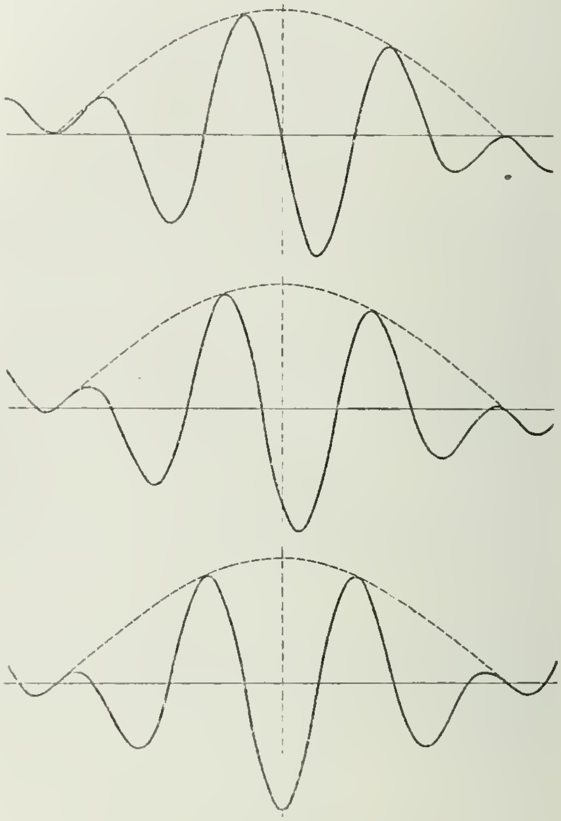


Fig. 22.

For full-pitch coils series (57) to (62) may be used, the values of the various coefficients being obtained readily from Figs. 7 and 9, or 11 and 12, the values depending both upon $Q$, the number of slots per pole, and upon the ratio of the slot width to the slot-pitch.

So far as the M.M.F. ripples are concerned, the remarks made for the case of a uniformly distributed winding may also be applied to this case, but the ripples will in general be more pronounced, especially in the case of the harmonics of orders $2Q \pm 1$ and $4Q \pm 1$, for which the value of the factor $f_{wp}$ differs but little from unity.

---

* This series is true for all cases if the origin is taken at a point between successive phase bands, as already indicated, and, in the case when $N$ is an odd number, if only the terms involving an even multiple of $N$ are included.

### TABLE 6.

*The Amplitudes of the M.M.F. Components established by Normal Full-pitch Polyphase Windings—in Slotted Armatures.*

The amplitude of the component is obtained by the product of the virtual value of the armature ampere-wires per pole, $(I_a Z_a)/(2p_m)$, and the constant obtained from the table below, $\lambda = 0{\cdot}4\,\gamma$.

| Order of Harmonic | 6 slots per pole | | | 9 slots per pole | | |
|---|---|---|---|---|---|---|
| | $N = 3$ | $N = 4$ | $N = 6$ | $N = 3$ | $N = 6$ | $N = 9$ |
| 1 | 0·375 | 0·409 | 0·434 | 0·374 | 0·432 | 0·443 |
| 3 | 0 | 0·0497 | 0 | 0 | 0 | 0 |
| 5 | 0·0192 | 0·0210 | 0·0222 | 0·0166 | 0·0190 | 0 |
| 7 | 0·0131 | 0·0143 | 0·0151 | 0·0093 | 0·011 | 0 |
| 9 | 0 | 0·0143 | 0 | 0 | 0 | 0 |
| 11 | 0·0272 | 0·0295 | 0·0314 | 0·0057 | 0·0065 | 0 |
| 13 | 0·0218 | 0·0226 | 0·0240 | 0·0056 | 0·0064 | 0 |
| 15 | 0 | 0·0045 | 0 | 0 | 0 | 0 |
| 17 | 0·0034 | 0·0036 | 0·0038 | 0·0178 | 0·0198 | 0·0203 |
| 19 | 0·0024 | 0·0027 | 0·0028 | 0·0144 | 0·0166 | 0·0170 |
| 21 | 0 | 0·0026 | 0 | 0 | 0 | 0 |
| 23 | 0·0046 | 0·0050 | 0·0053 | 0·0019 | 0·0027 | 0 |
| 25 | 0·0029 | 0·0031 | 0·0033 | 0·0016 | 0·0018 | 0 |

| | 12 slots per pole | | | 15 slots per pole | |
|---|---|---|---|---|---|
| | $N = 3$ | $N = 4$ | $N = 6$ | $N = 3$ | $N = 6$ |
| 1 | 0·373 | 0·405 | 0·431 | 0·373 | 0·430 |
| 3 | 0 | 0·0458 | 0 | 0 | 0 |
| 5 | 0·0158 | 0·0172 | 0·0183 | 0·0155 | 0·0179 |
| 7 | 0·0080 | 0·0088 | 0·0094 | 0·0082 | 0·0095 |
| 9 | 0 | 0·0061 | 0 | 0 | 0 |
| 11 | 0·0042 | 0·0046 | 0·0049 | 0·0038 | 0·0043 |
| 13 | 0·0035 | 0·0038 | 0·0040 | 0·0029 | 0·0034 |
| 15 | 0 | 0·0024 | 0 | 0 | 0 |
| 17 | 0·0031 | 0·0034 | 0·0037 | 0·0022 | 0·0025 |
| 19 | 0·0036 | 0·0039 | 0·0041 | 0·0020 | 0·0023 |
| 21 | 0 | 0·0052 | 0 | 0 | 0 |
| 23 | 0·0126 | 0·0138 | 0·0145 | 0·0022 | 0·0025 |
| 25 | 0·0085 | 0·0093 | 0·0098 | 0·0026 | 0·0030 |
| 29 | — | — | — | 0·0099 | 0·0115 |
| 31 | — | — | — | 0·0089 | 0·0103 |

| | 18 slots per pole | | | | |
|---|---|---|---|---|---|
| | $N = 3$ | $N = 4$ | $N = 6$ | $N = 9$ | $N = 12$ |
| 1 | 0·372 | 0·405 | 0·430 | 0·441 | 0·445 |
| 3 | 0 | 0·0460 | 0 | 0 | 0 |
| 5 | 0·0163 | 0·0167 | 0·0177 | 0 | 0 |
| 7 | 0·0080 | 0·0088 | 0 | 0 | 0 |
| 9 | 0 | 0·0058 | 0 | 0 | 0 |
| 11 | 0·0035 | 0·0038 | 0·0041 | 0 | 0·0042 |
| 13 | 0·0026 | 0·0029 | 0·0031 | 0 | 0·0032 |
| 15 | 0 | 0·0023 | 0 | 0 | 0 |
| 17 | 0·0018 | 0·0020 | 0·0021 | 0·0021 | 0 |
| 19 | 0·0016 | 0·0017 | 0·0019 | 0·0019 | 0 |
| 21 | 0 | 0·0016 | 0 | 0 | 0 |
| 23 | 0·0014 | 0·0015 | 0·0016 | 0 | 0·0017 |
| 25 | 0·0013 | 0·0014 | 0·0015 | 0 | 0·0016 |
| 35 | 0·0082 | 0·0089 | 0·0095 | 0·0097 | 0·0098 |
| 37 | 0·0075 | 0·0082 | 0·0087 | 0·0089 | 0·0089 |

An average value for the ratio of the slot width to the slot-pitch, in the case of synchronous converters, is 0·4. Tables have therefore been prepared by the author, showing the relative values of the amplitudes of the various harmonics for typical values of $N$ and $Q$, and based upon this ratio.

In Table 6, $N$ denotes the number of complete coil-groups per pair of poles in the case of two-layer windings, i.e. with synchronous converters $N$ denotes the number of slip-rings.

For single-layer full-pitch windings, $N$ denotes twice the number of phases of the winding, e.g. for a three-phase winding the constants are tabulated under $N = 6$.

When the number of coil groups per pair of poles is even, the data tabulated hold for single-layer windings in which the coil span is $(N - 1)\pi/N$ electrical radians. For a normal two-phase winding the constants are thus tabulated under $N = 4$.

*Single-layer windings.*—The general expressions given for the M.M.F. distribution of a polyphase winding, (55) and (56), hold for all types of winding. The main difference between a single-layer and the corresponding double-layer winding is that the spread of the coil-side, $\pi/N$, with the former is one-half of that, $2\pi/N$ with the latter.

With single-layer windings concentric coils are very commonly used; the displacement between corresponding coil-sides of adjacent coils is $2\pi/N$, and the spread of the coil-side is $\pi/N$, so that it is possible to employ coils having any span that will conform to $2\alpha_1 = (2M - 1)\pi/N$, $M$ being any integer. For example, when $N = 3$ the mean span of the coils may be $\pi/3$, $\pi$, $5\pi/3$, $7\pi/3$, $3\pi$, etc.; when $N = 4$ the span may be $\pi/4$, $3\pi/4$, $5\pi/4$, $7\pi/4$, etc.; and when $N = 6$ the span may be $\pi/6$, $\pi/2$, $5\pi/6$, $7\pi/6$, etc. Full-pitch coils can thus be used if the number of phases of the winding is an odd number, but not if it is even.

In general, when $N$ is odd, full-pitch coils are used, and when $N$ is even, the span of coils is invariably $(N - 1)\pi/N$ for a normal concentric winding.*

The values of the various factors, $f_1'$, etc., with single-layer windings will be identical with those obtaining for the $2N$-phase two-layer winding with the same slotting.

When $N$ is odd the only higher harmonics present are those of orders $2MN \pm 1$, for full-pitch coils, so that the M.M.F. distribution due to a single-layer winding with an odd number of phases is identical with that of the corresponding full-pitch two-layer winding of double the number of phases.

When $N$ is even and the coil span is $(N - 1)\pi/N$, the chording factor for the $(MN \pm 1)$th harmonic is $\cos\,(MN \pm 1)s\gamma_1$, the winding factor is

$$[\sin s(MN \pm 1)\gamma_1]/[s \sin\,(MN \pm 1)\gamma_1]$$

and their product is

$$[\sin 2s(MN \pm 1)\gamma_1]/[2s \sin\,(MN \pm 1)\gamma_1]$$

This latter is identical with the winding factor for the corresponding two-layer full-pitch winding.

As a result, the data tabulated for two-layer windings apply also to the case of single-layer windings of normal types, the only reservations being that when $N$ is odd the data corresponding to $2N$ coils per pair of poles should be taken, as indicated below the tables.

---

* Occasionally, when $N = 6$, a mean span of $\pi/2$ electrical radians is used.

So far as the production of air-gap field is concerned, it follows also that when $N$ is an odd number the effect of a single-layer $N$-phase winding is identical with that of a single-layer winding with $2N$ coils per pair of poles, each spanning $(N - 1)\pi/N$ radians.

*Fractional pitch, or chorded, windings.*—The general expression for the M.M.F. developed by a polyphase winding, as given in (56), is:—

$$\begin{aligned} x = \frac{NX_{max.}}{\pi} \Big[ \Big\{ & f_1' \sin \alpha_1 \cos (\omega t - \theta_1) \\ & + \frac{1}{N+1} f_{N+1}' \sin (N+1)\alpha_1 \cos (\omega t - \overline{N+1}\theta_1) + \ldots \Big\} \\ & + \Big\{ \frac{1}{N-1} f_{N-1}' \sin (N-1)\alpha_1 \cos (\omega t + \overline{N-1}\theta_1) + \ldots \Big\} \Big] \end{aligned}$$

The effect of chording the winding can therefore at once be determined by inserting in the above series the appropriate value for the half-span $\alpha_1$ of the coil, expressed in electrical measure to correspond to the main number of poles.

In cases where the amount of chording is very small, as for example in the case of a winding chorded by one slot-pitch, it is more convenient to express the above series in terms of the amount by which the winding is chorded. Thus, for example, when $N$ is an even number the M.M.F. distribution due to a polyphase winding may be represented by:—

$$\begin{aligned} x = \frac{NX_{max.}}{\pi} \Big[ \Big\{ & f_1' \cos \delta_1 \cos (\omega t - \theta_1) \\ & + \frac{1}{N+1} f_{N+1}' \sin (N+1)\frac{\pi}{2} \cos (N+1)\delta_1 \cos (\omega t - \overline{N+1}\theta_1) + \ldots \Big\} \\ & + \Big\{ \frac{1}{N-1} f_{N-1}' \sin (N-1)\frac{\pi}{2} \cos (N-1)\delta_1 \cos (\omega t + \overline{N-1}\theta_1) + \ldots \Big\} \Big] \end{aligned}$$

where $2\delta_1 = \pi - 2\alpha_1$, as in series (2).

The values of the amplitudes of the various higher harmonics are therefore obtained from those for the corresponding full-pitch winding by multiplying by the appropriate chording factors, which latter are simply the cosines of one-half of the angle by which the winding is chorded, expressed in electrical measure to accord with the particular harmonic under investigation.

When $N$ is an odd number the series for the M.M.F. distribution is:—

$$\begin{aligned} x = \frac{NX_{max.}}{\pi} \Big[ \Big\{ & f_1' \cos \delta_1 \cos (\omega t - \theta_1) - \frac{1}{N+1} f_{N+1}' \\ & \times \cos (N+1)\frac{\pi}{2} \sin (N+1)\delta_1 \cos (\omega t - \overline{N+1}\theta_1) \\ & + \frac{1}{2N+1} f_{2N+1}' \sin (2N+1)\frac{\pi}{2} \times \cos (2N+1)\delta_1 \\ & \times \cos (\omega t - \overline{2N+1}\theta_1) - \ldots \Big\} \\ & + \Big\{ -\frac{1}{N-1} f_{N-1}' \cos (N-1)\frac{\pi}{2} \sin (N-1)\delta_1 \\ & \times \cos (\omega t + \overline{N-1}\theta_1) \\ & + \frac{1}{2N-1} f_{2N-1}' \sin (2N-1)\frac{\pi}{2} \\ & \times \cos (2N-1)\delta_1 \cos (\omega t + 2\overline{N-1}\theta_1) - \ldots \Big\} \Big] \end{aligned}$$

The winding no longer spanning an exact pole-pitch, the even harmonics, i.e. of orders $(2M - 1)N \pm 1$, are not now eliminated.

For the odd harmonics, the chording factor is again the cosine of the equivalent angle of chording, but for the even harmonics the factor is the sine of the angle of chording, in electrical measure corresponding to the particular harmonic under consideration.

In general, the effect of chording the winding is to reduce the relative importance of all the higher harmonics in the M.M.F. wave, with the exception of those of orders $2Q \pm 1$, $4Q \pm 1$, etc., for which the relative importance is the same as with full-pitch coils. The reduction is greatest, when $N$ is even, in the case of harmonics of orders $Q \pm 1$, $3Q \pm 1$, etc.

When the number of phases of the winding is even, no additional harmonics are introduced by chording the coils, but when $N$ is odd an important series of even harmonics is introduced.

Windings in which the coils are short-chorded by one slot-pitch are of common occurrence; the author has therefore thought fit to tabulate data relating to such windings. For other less common cases the formulæ here developed may be applied readily.

The values given in Table 7 correspond exactly to those given for the case of full-pitch coils, with the exception that the winding is taken to be chorded by one slot-pitch. The tables relate to the case of two-layer windings and for a slot width = 0·4 × slot-pitch.

## IX. POLE-CHANGING WINDINGS.

It follows at once from the series* for the resulting magnetomotive force developed by a single coil, that, with certain exceptions depending upon the span of the coil, any given coil can be utilized in the production of a magnetic field of any desired number of poles. The exceptions occur only when $\sin p\alpha = 0$, i.e. when the product of the number of pairs of poles and the span of the coil is a multiple of $2\pi$. For the case of a complete coil group in which the coil-side is distributed in two or more slots, further exceptions occur when $\sin p\beta = 0$. Quite independent of the mean span of the coil group, therefore, the coil group cannot be utilized in the formation of a magnetic field for which the product of the number of poles and the spread of the coil-side is a multiple of $4\pi$.

Further, it has been shown that, for $m$ similar coils, or coil groups, spaced uniformly around an armature:—

(1) If all the coils carry currents of the same magnitude and in the same direction, the fundamental harmonic of the resulting M.M.F. distribution corresponds to a $2m$-pole field.

(2) If polyphase currents are supplied to the $m$ coils, such that the phase displacement $2\phi$ between currents in successive coils is a multiple of the angle of mechanical phase displacement between neighbouring coils, i.e. $2\phi = q2\pi/m$, the main component of the M.M.F. distribution is determined by the value of $q$. Normally, the two most important components are the $2q$-pole

---

* Cf. series (3), page 751.

TABLE 7.

*The Amplitudes of the M.M.F. Components established by Normal Two-layer Polyphase Windings Short-chorded by One Slot-pitch.* $\lambda = 0 \cdot 4\gamma$.

The amplitude is given by the product of $(I_a Z_a)/2p_m$ and the factor tabulated below.

| Order of harmonic | $N = 3$ | | | | |
|---|---|---|---|---|---|
| | $Q = 6$ | $Q = 9$ | $Q = 12$ | $Q = 15$ | $Q = 18$ |
| 1 | 0·364 | 0·369 | 0·370 | 0·371 | 0·371 |
| 2 | 0·0483 | 0·0324 | 0·0229 | 0·0195 | 0·0163 |
| 4 | 0·0237 | 0·0158 | 0·0114 | 0·0097 | 0·0081 |
| 5 | 0·0050 | 0·0107 | 0·0125 | 0·0133 | 0·0148 |
| 7 | 0·0034 | 0·0039 | 0·0049 | 0·0081 | 0·0066 |
| 8 | 0·0107 | 0·0076 | 0·0056 | 0·0048 | 0·0040 |
| 10 | 0·0080 | 0·0060 | 0·0044 | 0·0038 | 0·0032 |
| 11 | 0·0263 | 0·0019 | 0·0006 | 0·0015 | 0·0020 |
| 13 | 0·0210 | 0·0036 | 0·0005 | 0·0006 | 0·0011 |
| 14 | 0·0047 | 0·0039 | 0·0030 | 0·0026 | 0·0022 |
| 16 | 0·0034 | 0·0033 | 0·0025 | 0·0023 | 0·0019 |
| 17 | 0·0009 | 0·0176 | 0·0016 | 0·0005 | 0·0002 |
| 19 | 0·0006 | 0·0142 | 0·0025 | 0·0008 | 0·0001 |
| 20 | 0·0020 | 0·0023 | 0·0019 | 0·0017 | 0·0015 |
| 22 | 0·0014 | 0·0019 | 0·0017 | 0·0015 | 0·0013 |
| 23 | 0·0044 | 0·0008 | 0·0125 | 0·0016 | 0·0006 |
| 25 | 0·0028 | 0·0005 | 0·0084 | 0·0023 | 0·0007 |

| | $N = 6$ | | | | |
|---|---|---|---|---|---|
| | $Q = 6$ | $Q = 9$ | $Q = 12$ | $Q = 15$ | $Q = 18$ |
| 1 | 0·419 | 0·426 | 0·427 | 0·427 | 0·428 |
| 5 | 0·0058 | 0·0122 | 0·0145 | 0·0155 | 0·0161 |
| 7 | 0·0039 | 0·0038 | 0·0067 | 0·0071 | 0·0075 |
| 11 | 0·0303 | 0·0022 | 0·0006 | 0·0017 | 0·0024 |
| 13 | 0·0232 | 0·0040 | 0·0005 | 0·0007 | 0·0013 |
| 17 | 0·0010 | 0·0195 | 0·0023 | 0·0005 | 0·0002 |
| 19 | 0·0007 | 0·0164 | 0·0033 | 0·0009 | 0·0002 |
| 23 | 0·0051 | 0·0017 | 0·0144 | 0·0019 | 0·0007 |
| 25 | 0·0032 | 0·0006 | 0·0092 | 0·0026 | 0·0009 |

| | $N = 4$ | | |
|---|---|---|---|
| | $Q = 6$ | $Q = 12$ | $Q = 18$ |
| 1 | 0·395 | 0·401 | 0·403 |
| 3 | 0·0035 | 0·0423 | 0·0445 |
| 5 | 0·0054 | 0·0137 | 0·0151 |
| 7 | 0·0037 | 0·0054 | 0·0072 |
| 9 | 0·0101 | 0·0023 | 0·0041 |
| 11 | 0·0185 | 0·0006 | 0·0022 |
| 13 | 0·0218 | 0·0005 | 0·0012 |
| 15 | 0·0032 | 0·0011 | 0·0006 |
| 17 | 0·0009 | 0·0021 | 0·0002 |
| 19 | 0·0007 | 0·0031 | 0·0001 |
| 21 | 0·0018 | 0·0048 | 0·0004 |
| 23 | 0·0048 | 0·0137 | 0·0006 |
| 25 | 0·0030 | 0·0092 | 0·0008 |

| | $N = 9$ | | Order of harmonic | $N = 12$ |
|---|---|---|---|---|
| | $Q = 9$ | $Q = 18$ | | $Q = 18$ |
| 1 | 0·437 | 0·439 | 1 | 0·443 |
| 8 | 0·0097 | 0·0047 | 11 | 0·0024 |
| 10 | 0·0078 | 0·0038 | 13 | 0·0014 |
| 17 | 0·0200 | 0·0002 | 23 | 0·0007 |
| 19 | 0·0173 | 0·0002 | 25 | 0·0009 |

component rotating synchronously in a positive direction, and the $2(m - q)$-pole component rotating in a negative direction.

(3) When adjacent coils carry currents of the same magnitude but displaced by 180° in phase, the fundamental harmonic of the resulting M.M.F. corresponds to $m$ poles.

It follows therefore that there are two main methods of changing the number of main poles established by a given winding, viz.

(A) By altering the number of coil groups; and

(B) By retaining the original number, $m$, of coil groups, but altering the phase displacement, $2\phi$, of the currents in successive coils of the winding.

Both these methods are in use in practice.

Method A can best be applied in the case of two-layer barrel windings, in which all the slot coils have the same span. By suitably connecting the coil-ends a normal barrel winding can be arranged for various numbers of poles, and with single-phase windings no great difficulty would be thus experienced. With three-phase windings the possibilities of the method are much more limited owing to the need of conserving the correct balance of the phases.

Method B can be applied equally well with all types of winding, single-layer or double-layer, barrel or concentric.

It will be a convenience to deal separately with the more common cases of change-pole windings met with in practice, and to show how the theory developed in the present paper can be applied to such cases.

*Case* I. *Numbers of poles in the ratio* 2 : 1.—For this ratio, a winding corresponding to a normal hemitropic single-layer winding for the larger number of poles is often employed. It is made suitable for the smaller number of poles by reversing the current in alternate coils of each phase group.

So far as a single-phase winding is concerned, and hence also for any one phase of a polyphase winding, the principle of this method follows at once from Section IV of the paper. For if $m$ is the total number of coils, each spanning $\pi/m$ radians, when all the coils carry current in the same direction the M.M.F. distribution becomes :—

$$x = \frac{2X}{\pi}\left\{f_m \cos m\theta - \tfrac{1}{3} f_{3m} \cos 3m\theta + \tfrac{1}{5} f_{5m} \cos 5m\theta - \dots\right\}$$

[from (39)]

and when adjacent coils carry current in opposite directions the M.M.F. distribution is given by :—

$$x = \frac{4X}{\pi}\left\{f_{m/2} \sin \frac{\pi}{4} \cos \frac{m\theta}{2} + \tfrac{1}{3} f_{3m/2} \sin \frac{3\pi}{4} \cos \frac{3m\theta}{2} + \dots\right\}$$

[from (38)]

$$= 0 \cdot 707 \times \frac{4X}{\pi}\left\{f_{m/2} \cos \frac{m\theta}{2} + \tfrac{1}{3} f_{3m/2} \cos \frac{3m\theta}{2} - \dots\right\} \quad (69)$$

Thus if the winding is a normal full-pitch winding for the large number of poles, it becomes considerably chorded for the small number of poles, the chording factor $\sin p\alpha$ being $0\cdot707$ * for each of the harmonics present in the M.M.F. distribution.

The fundamental harmonic of series (39) corresponds to $m$ pole-pairs, whereas that of series (69) is for $m/2$ pole-pairs.

With polyphase windings it is necessary not merely to halve the number of poles produced by each phase of the winding, but, in addition, to arrange that the direction of rotation of the main M.M.F. component shall be the same for both numbers of poles, and it is of course essential that the main M.M.F. component shall be of constant amplitude, i.e. that the rotating field due to this component shall not be "elliptical."

The method in use for halving the number of poles of a normal hemitropic single-layer polyphase winding does not, therefore, merely involve reversing the currents in alternate coils of each of the phase groups. The method should rather be regarded as falling directly into classification B, the number of poles being halved by reducing the phase displacement between the currents in adjacent coils to one-half of the value obtaining for the larger number of poles. Thus, in the case of a normal three-phase winding of the hemitropic type with concentric coils, for a normal full-pitch 8-pole winding there will be $3 \times 4 = 12$ coils, and the currents in neighbouring coils will be displaced by $2\pi/3$. To convert the winding into a 4-pole winding this phase displacement is reduced to $\pi/3$, i.e. the winding is converted into a six-phase hemitropic winding having 4 poles.

For the mechanical displacement between the coils we have $2\psi = 2\pi/12$. Hence for the 8-pole grouping, since $2\phi = 2\pi/3$, $q = 4$, and the M.M.F. at any point on the armature circumference is given by:—

$$x = \frac{3X_{max.}}{\pi}\left[\left\{f_4 \sin\frac{\pi}{2}\cos(\omega t - 4\theta) + \tfrac{1}{7}f_{28}\sin\frac{7\pi}{2}\cos(\omega t - 28\theta) + \ldots\right\} + \left\{\tfrac{1}{5}f_{20}\sin\frac{5\pi}{2}\cos(\omega t + 20\theta) + \tfrac{1}{11}f_{44}\sin\frac{11\pi}{2}\cos(\omega t + 44\theta) + \ldots\right\}\right]$$

For the 4-pole grouping, $2\phi = \pi/3$ and $q = 2$, so that the M.M.F. is now represented by:—

$$x = \frac{6X_{max.}}{\pi}\left[\left\{f_2 \sin\frac{\pi}{4}\cos(\omega t - 2\theta) + \tfrac{1}{7}f_{14}\sin\frac{7\pi}{4}\cos(\omega t - 14\theta) + \ldots\right\} + \left\{\tfrac{1}{5}f_{10}\sin\frac{5\pi}{4}\cos(\omega t + 10\theta) + \tfrac{1}{11}f_{22}\sin\frac{11\pi}{4}\cos(\omega t + 22\theta) + \ldots\right\}\right]$$

Again, for a normal full-pitch 8-pole winding, the chording factor becomes $0\cdot707$ for each of the components of the 4-pole M.M.F.

When the number of phases of the supply system is odd there is no particular difficulty in arranging for the phase displacement between the currents in adjacent coils to be one-half of that between phases of the supply system. Fig. 20 indicates the method in the case of a five-phase supply.

With symmetrical polyphase systems, if the number of phases of the supply is even it is not possible to halve the phase difference without employing a phase transformer.

In the case of the 8-pole three-phase winding discussed above, the amplitude of the fundamental harmonic is:—

$$\frac{3X_{max.}}{\pi}f_4 \sin 4\alpha = \frac{3X_{max.}}{\pi}f_4$$

and for the 4-pole arrangement of the winding the amplitude is:—

$$\frac{6X_{max.}}{\pi}f_2 \sin 2\alpha = \frac{6X_{max.}}{\pi}f_2\, 0\cdot707$$

The ratio is thus:—

$$= 2 \times 0\cdot707\frac{f_2}{f_4} \doteqdot 2 \times 0\cdot707 \times \frac{0\cdot99}{0\cdot96} \doteqdot 1\cdot46$$

So far as the production of the 4-pole M.M.F. is concerned, therefore, the winding is only 73 per cent as effective as a normal full-pitch winding.

*Case 2. Numbers of poles in the ratio* 4 : 3.—This ratio is commonly employed in polyphase traction motors, methods A and B both being used.

In the first method it is necessary to arrange that $m$, the number of coil groups, can be altered in the ratio of 4 : 3, and hence the spread of the phase band in the ratio of 3 : 4. It is therefore inconvenient to apply a concentric winding, but a two-layer barrel winding is well suited.

With a single-phase winding thus arranged for pole-changing it is obvious that certain of the coils will carry current in the same direction with both arrangements of the winding: for the other coils the current with the large number of poles will be in the opposite direction to that obtaining with the smaller number. Hence the winding may be divided into two parts; by joining these parts in "straight series" the smaller number of poles is obtained, and the larger number by connecting the two parts in "reversed series." With a single-phase winding the necessary controller arrangements are thus very simple, but with polyphase windings a much greater subdivision of the winding is necessary, and the controller becomes rather elaborate. It may readily be shown that the coils must be divided into as many groups as the square of the number of phases if $N$ is odd, and one-half of that number if $N$ is even. Thus when $N = 4$, i.e. with a winding suitable for a two-phase supply, 8 groups are necessary, and when $N = 6$, i.e. a winding suitable for a three-phase supply, 18 groups are necessary.

---

* The various factors $f_p$, $\sin p\alpha$ used in the series for the M.M.F. have also to be used in E.M.F. calculations with such windings.

In spite of the large number of leads that have to be taken out to the pole-changing controller, this method of pole-changing is employed in some of the most recent three-phase locomotives.

The series for the resulting M.M.F. distribution follow at once from (55), and for the case of a winding arranged for 6 and 8 poles, respectively, are :—

$$\begin{aligned} x = \frac{8X_{max.}}{\pi}\Big[&\Big\{f_3 \sin 3a \cos(\omega t - 3\theta) \\ &+ \tfrac{1}{7} f_{21} \sin 21a \cos(\omega t - 21\theta) + \ldots\Big\} \\ &+ \Big\{\tfrac{1}{5} f_{15} \sin 15a \cos(\omega t + 15\theta) \\ &+ \tfrac{1}{11} f_{33} \sin 33a \cos(\omega t + 33\theta) + \ldots\Big\}\Big] \end{aligned}$$

and

$$\begin{aligned} x = \frac{6X_{max.}}{\pi}\Big[&\Big\{f_4 \sin 4a \cos(\omega t - 4\theta) \\ &+ \tfrac{1}{7} f_{28} \sin 28a \cos(\omega t - 28\theta) + \ldots\Big\} \\ &+ \Big\{\tfrac{1}{5} f_{20} \sin 20a \cos(\omega t + 20\theta) \\ &+ \tfrac{1}{11} f_{44} \sin 44a \cos(\omega t + 44\theta) + \ldots\Big\}\Big] \end{aligned}$$

The value of $2a$, the angle spanned by the individual slot-coils (in mechanical measure), will be chosen to suit best the particular duty the machine has to perform ; normally, the value corresponding to an exact pole-pitch for the larger number of poles will be satisfactory. The winding then becomes a full-pitch winding for the larger number of poles, and a $\frac{3}{4}$, fractional-pitch winding for 6-pole operation.

For a winding arranged in 72 slots, and for a slot width equal to one-half of the slot-pitch the above series thus becomes :—

$$\begin{aligned} x = \frac{6X_{max.}}{\pi}\Big[&\Big\{0{\cdot}959 \cos(\omega t - 4\theta) \\ &- \tfrac{1}{7} \times 0{\cdot}166 \cos(\omega t - 28\theta) \\ &+ \tfrac{1}{13} \times 0{\cdot}174 \cos(\omega t - 52\theta) + \ldots\Big\} \\ &+ \Big\{\tfrac{1}{5} \times 0{\cdot}211 \cos(\omega t + 20\theta) \\ &- \tfrac{1}{11} \times 0{\cdot}151 \cos(\omega t + 44\theta) + \ldots\Big\}\Big] \quad . \quad (70)^* \end{aligned}$$

for 8-pole operation,

and

$$\begin{aligned} x = \frac{8X_{max.}}{\pi}\Big[&\Big\{0{\cdot}884 \cos(\omega t - 3\theta) \\ &- \tfrac{1}{7} \times 0{\cdot}141 \cos(\omega t - 21\theta) \\ &+ \tfrac{1}{13} \times 0{\cdot}043 \cos(\omega t - 39\theta) - \ldots\Big\} \\ &+ \Big\{\tfrac{1}{5} \times 0{\cdot}077 \cos(\omega t + 15\theta) \\ &- \tfrac{1}{11} \times 0{\cdot}044 \cos(\omega t + 33\theta) + \ldots\Big\}\Big] \quad . \quad (71)^* \end{aligned}$$

for 6-pole working.

To apply method B in this case it is necessary to have some means of altering in the ratio of 4 : 3 the phase displacement between the currents in adjacent coils.

An obvious pair of suitable values is given by $2\phi = 2\pi/3$ and $2\phi = \pi/2$, values which are at once obtainable from a three-phase and a two-phase supply, respectively. For example, a normal hemitropic three-phase winding has 12 coils for an 8-pole machine, and a normal 6-pole winding for a machine working on a two-phase system has also 12 coils. In fact, if single-layer windings are used in both cases the actual arrangement of the coils is identical, excepting only the connections between coils, etc.

With 12 coils the effect of varying the phase displacement between the currents in adjacent coils has already been discussed and the relevant data tabulated. The value of $q$ for the 8-pole arrangement is 4, and, for the 6-pole arrangement, 3.

The series for the resulting M.M.F. thus become :—

$$\begin{aligned} x = \frac{3X_{max.}}{\pi}\Big[&\Big\{f_4 \cos(\omega t - 4\theta) + \tfrac{1}{7} f_{28} \cos(\omega t - 28\theta) \\ &+ \tfrac{1}{13} f_{52} \cos(\omega t - 52\theta) + \ldots\Big\} \\ &+ \Big\{\tfrac{1}{5} f_{20} \cos(\omega t + 20\theta) \\ &+ \tfrac{1}{11} f_{44} \cos(\omega t + 44\theta) + \ldots\Big\}\Big] \end{aligned}$$

for the 8-pole arrangement,

$$\begin{aligned} \text{and} \quad x = \frac{4X_{max.}}{\pi}\Bigg[&\Bigg\{f_3 \sin\frac{3\pi}{8} \cos(\omega t - 3\theta) \\ &+ \tfrac{1}{5} f_{15} \sin\frac{15\pi}{8} \cos(\omega t - 15\theta) + \ldots\Bigg\} \\ &+ \Bigg\{\tfrac{1}{3} f_9 \sin\frac{9\pi}{8} \cos(\omega t + 9\theta) \\ &+ \tfrac{1}{7} f_{21} \sin\frac{21\pi}{8} \cos(\omega t + 21\theta) + \ldots\Bigg\}\Bigg] \end{aligned}$$

for the 6-pole arrangement,

and for the case in which the mean span of the coil corresponds to an exact pole-pitch with the larger number of poles, i.e. for a normal 8-pole single-layer three-phase winding.

For the case of a 72-slot winding previously considered, the resulting M.M.F. for the 8-pole arrangement is exactly as in series (70). For the 6-pole arrangement, the M.M.F. will now be represented by :—

$$\begin{aligned} x = \frac{4X_{max.}}{\pi}\Big[&\Big\{0{\cdot}900 \cos(\omega t - 3\theta) - \tfrac{1}{5} \times 0{\cdot}191 \cos(\omega t - 15\theta) \\ &+ \tfrac{1}{9} \times 0{\cdot}121 \cos(\omega t - 27\theta) - \ldots\Big\} \\ &+ \Big\{\tfrac{1}{3} \times 0{\cdot}305 \cos(\omega t + 9\theta) \\ &- \tfrac{1}{7} \times 0{\cdot}143 \cos(\omega t + 21\theta) + \ldots\Big\}\Big]^* \end{aligned}$$

The application of method B to this case thus involves the use of a phase transformer ; in the case of a three-phase supply the Scott method is utilized to obtain the two-phase currents necessary for operation with the smaller number of poles.

*Case* 3. *Windings for operation at many different numbers of poles. The Creedy motor.*—In the previous case it is of course possible, as shown in Table 4, to utilize the winding with 12 coils for 4, 6 or 8 poles, the winding being fed with six-phase, four-phase and three-phase currents, respectively, involving the use of a phase transformer for the 6-pole connection. Mr. Creedy has developed a method of speed control of induction motors in which the number of poles can be varied in steps of 2 over a very wide range, especially in the case of low-speed motors. The method falls into classification B, the change in the number of poles being effected entirely by changing the displacement between the currents in adjacent phases of the winding, a very fine gradation in the displacement being obtained by employing a supply having a very large number of phases.

---

* $X_{max.}$ is taken to be the value of the M.M.F. per coil for the 8-pole winding, so that if the value of the current is maintained, $4X_{max}/3$ is the corresponding value for the 6-pole winding.

In contrasting this case with the following it must be borne in mind that $X$ for the single-layer winding there discussed will of necessity be twice the value for the corresponding two-layer winding having double the number of coils.

* Cf. series 71.

TABLE 8.

*The Amplitudes of the M.M.F. Components Established by a Polyphase Winding having* 31 *Coils and fed with Currents having Various Phase Displacements in Successive Coils, as in the Creedy Motor.*

Number of slots = 165; coil span = 11 slot-pitches.

| Number of pole-pairs* | | Winding factors, etc. | | | | Amplitude of M.M.F. | |
|---|---|---|---|---|---|---|---|
| | | $f_{wp}$ | $f_{sp}$ | $\sin p\alpha$ | $f_p \sin p\alpha$ | $\frac{I_a Z_a}{2p} \times$ | $I_a Z_a \times$ |
| 5 | | 0·963 | 1·000 | 0·866 | 0·834 | 0·375 | 0·0375 |
| | 26 | 0·254 | 0·990 | 0·743 | 0·185 | — | 0·0016 |
| 36 | | 0·091 | 0·981 | 0·951 | 0·085 | — | 0·0005 |
| 6 | | 0·949 | 1·000 | 0·951 | 0·902 | 0·406 | 0·0338 |
| | 25 | 0·300 | 0·990 | 0·866 | 0·257 | — | 0·0023 |
| 37 | | 0·115 | 0·980 | 0·995 | 0·112 | — | 0·0007 |
| 7 | | 0·931 | 0·999 | 0·995 | 0·925 | 0·416 | 0·0297 |
| | 24 | 0·342 | 0·991 | 0·951 | 0·323 | — | 0·0030 |
| 38 | | 0·139 | 0·979 | 0·995 | 0·135 | — | 0·0018 |
| 8 | | 0·909 | 0·999 | 0·995 | 0·903 | 0·407 | 0·0254 |
| | 23 | 0·384 | 0·991 | 0·995 | 0·379 | — | 0·0037 |
| 39 | | 0·161 | 0·978 | 0·951 | 0·150 | — | 0·0009 |
| 9 | | 0·886 | 0·999 | 0·951 | 0·822 | 0·370 | 0·0206 |
| | 22 | 0·426 | 0·993 | 0·995 | 0·421 | — | 0·0043 |
| 40 | | 0·180 | 0·976 | 0·886 | 0·152 | — | 0·0009 |
| 10 | | 0·861 | 0·999 | 0·866 | 0·745 | 0·335 | 0·0168 |
| | 21 | 0·468 | 0·993 | 0·951 | 0·443 | — | 0·0047 |
| 41 | | 0·197 | 0·975 | 0·743 | 0·143 | — | 0·0008 |
| 11 | | 0·834 | 0·998 | 0·743 | 0·626 | 0·282 | 0·0128 |
| | 20 | 0·510 | 0·994 | 0·866 | 0·439 | — | 0·0049 |
| 42 | | 0·212 | 0·973 | 0·407 | 0·084 | — | 0·0005 |

* For the components rotating in a positive direction, the number of poles is placed to the left of the column, and to the right for negative rotation.

The amplitude of the main harmonic is given in terms of the virtual value of the ampere-conductors per pole, the number of poles being based upon that harmonic.

The final column gives the amplitudes of the various components in terms of the total ampere-conductors on the armature.

The mathematical theory of the M.M.F. developed by the Creedy motor follows at once from (54). By taking $m$ fairly large and at the same time making it a prime number, a satisfactory winding can be obtained with various values for the main number of poles if an $m$-phase supply is used. A phase transformer is thus necessary, but if it is used in the form of an auto-transformer it is of relatively small dimensions.

The only higher harmonics present in the wave of resulting M.M.F. are those of orders $Mm + q$, rotating in the positive direction, and those of orders $Mm - q$, rotating in a negative direction. With the large values of $m$ put forward by Mr. Creedy, the resulting M.M.F. wave is thus remarkably pure, and, under the assumptions made in the present paper, the resulting flux distribution will be practically sinusoidal if $q$ is very small in comparison with $m$.

When $m$ is a prime number, the higher harmonics, excepting only in the case of $q = 1$, will not be multiples of $q$, i.e. of the fundamental number of poles. As a result, the flux-distribution wave cannot be subdivided into $q$ similar parts as with a normal polyphase winding, but the field-form over one pole-pitch will have slightly different shapes for each of the $2q$ poles. The deviations are not likely to be appreciable unless $q$ approaches $m/2$.

Table 8 indicates the orders of the harmonics present with various values of $q$ for the case of $m = 31$, for a 165-slot winding, and with the slot width equal to one-half of the slot-pitch. The relative values of the amplitudes of the harmonics of orders $q$ and $Mm \pm q$ are given in Table 8, for the case when the mean span of the coil is 11 slot-pitches, corresponding to practically a full-pitch coil for 14 poles.

## X. THE EFFECTS OF SATURATION, HIGHER HARMONICS IN THE CURRENT-WAVE, ETC.

When the iron parts of the magnetic circuit absorb an appreciable portion of the magnetomotive force, the resulting difference of magnetic potential between stator and rotor at any point on the rotor circumference can no longer be obtained by summing the effects produced by the individual action of the separate coils. The variation in the degree of saturation of the teeth over the pole pitch, the effect of the flux leaking across the slots, and, in cases of highly saturated cores, the calculation of the exact effect of the saturation of the core, all further complicate the problem. Under such conditions, therefore, it becomes necessary to deal with each case on its own merits, and no general analytical or synthetical method is admissible.

C. C. Hawkins* has shown how the actual shape of the field-form can be obtained in the case of a cylindrical-field alternator, and Dr. F. T. Chapman† has discussed the problem as it affects the induction motor.

In general it may be taken that the effect of saturation will not invalidate the conclusions arrived at in the present paper so far as the main number of poles produced by any particular winding is concerned, although the amplitude of the fundamental harmonic in the resulting flux wave will be influenced largely by the degree of magnetic saturation. For the higher harmonics, however, both the orders present and their relative importance will be determined very largely by the degree of magnetic saturation. Harmonics absent in the flux-wave when the iron is totally unsaturated appear as the degree of saturation is increased, while others already present may be increased or decreased, the analysis of the wave-form changing with every change in value of the current in the coil. The author* has already illustrated this point in so far as the third harmonics in the M.M.F. of cylindrical-field alternators are concerned.

---

* HAWKINS, C. C., SMITH, S. P., and NEVILLE, S.: "Papers on the Design of Alternating-current Machinery."

† F. T. CHAPMAN: "The Air-gap Field of the Polyphase Induction Motor," *Electrician*, 1916, vol. 78, p. 9.

With polyphase windings the effect of magnetic saturation will be to reduce the importance of the periodic changes in the total resulting M.M.F., and to result, at the same time, in the wave-shape of the rotating flux distribution being more nearly constant, although departing very considerably from the pure sinusoidal form.

The current carried by the windings may also not be sinusoidal, but contain higher harmonics of considerable importance.

In many cases, such as in induction motors, the main reason for the current deviating from sinusoidal form is to be found in the fact that the reluctance of the iron parts is of importance. Under such conditions it is of little use to attempt to determine by any analytical mathematical method the effect of each individual current harmonic; saturation of the iron again renders futile any such attempt.

In the case of alternators and synchronous converters there is, however, often more justification in dealing separately with the effects of each of the current harmonics, especially in the case of harmonics of relatively low orders.

Let the current be represented by

$$i = I_{1max.} \cos \omega t + I_{2max.} \cos 2\omega t + I_{3max.} \cos 3\omega t + \ldots$$

so that the M.M.F. due to the $n$th current harmonic will be represented by $X_{nmax.} \cos n\omega t$.

Then the difference of magnetic potential between stator and rotor due to the sole action of the $n$th current harmonic in the case of a normal polyphase winding will be, from (54) :—

$$x_n = m\Big[\Big\{C_{nq} \cos (n\omega t - nq\theta) + C_{m+nq} \cos (n\omega t - \overline{m+nq}\theta) + \ldots\Big\} + \Big\{C_{m-nq} \cos (n\omega t + \overline{m-nq}\theta) + \ldots\Big\}\Big]$$

where $q$ is based upon the fundamental current harmonic.

The effect of any particular current harmonic is thus at once obtained in cases where the reluctance of the iron parts can be neglected.

In brief, the effect of the $n$th current harmonic is to cause the speed of rotation of the $p$th field component due to that harmonic to be $n\omega/p$ radians per sec. and at the same time to increase from $2\phi$ to $2n\phi$ the value of the phase displacement between the currents in neighbouring coils due to the $n$th harmonic.

The series for the effect of the $n$th current harmonic expressed in electrical measure to correspond to the fundamental of the main M.M.F. is thus :—

$$x_n = \frac{NX_{nmax.}}{\pi}\Bigg[\Big\{\frac{1}{n}f'_n \cos (n\omega t - n\theta_1) + \frac{1}{N+n}f'_{N+n} \sin (N+n)\frac{\pi}{2} \cos (n\omega t - \overline{N+n}\theta_1) + \ldots\Big\} + \Big\{\frac{1}{N-n}f'_{N-n} \sin (N-n)\frac{\pi}{2} \times \cos (n\omega t + \overline{N-n}\theta_1) + \ldots\Big\}\Bigg]$$

For a normal polyphase winding the field components due to the $n$th current harmonic will therefore be made up solely of those of orders $(MN + n)$ times the main number of poles rotating in a positive direction, and those of orders $MN - n$ rotating in a negative direction. For the general case $M$ is any integer, but for full-pitch coils when $N$ is an odd number only even values for $M$ must be taken, for the reasons previously stated.† As a result the field components due to the $n$th harmonic will in general be of different orders from those due to the fundamental.

Hence the wave-shapes of the M.M.F. due solely to the action of any particular current harmonic will, in general, differ from that due to the fundamental harmonic.

This is illustrated by Table 9, which shows the field components established in normal full-pitch polyphase windings by the various harmonics of the current wave. The direction of rotation of the various components is indicated.

The table relates to full-pitch single-layer windings when the number of coils per pair of poles, i.e. the number of phases, $N$, of the winding is odd. When $N$ is even the data relate either to full-pitch two-layer windings or to the normal single-layer winding having a coil span of $2\alpha = (N - 1) \times \pi/N$.

With two-layer windings with an odd number of phases, the spread of the coil-side is such as to eliminate all component M.M.F.'s of orders corresponding to any multiple of the number of phases. It will be seen from the table that such components are established only by current harmonics of orders corresponding to any multiple of the number of phases, hence with double-layer windings such current harmonics do not give rise to any resulting M.M.F.‡

Thus the third, fifth, seventh, ninth, etc., current harmonics do not produce any resultant M.M.F. with two-layer windings having, respectively, three, five, seven, nine, etc., phases.

With the corresponding single-layer windings these particular current harmonics give rise to both the normal and inverse rotating components of all fields of orders corresponding to any odd multiple of the order of the number of phases. That is, the $n$th current harmonic gives rise to a purely alternating M.M.F. when $n$ is any odd multiple of $N$, if $N$ is an odd number, and of $N/2$ if $N$ is an even number, for all cases except the two-layer winding with an odd number of coils per pair of poles.

---

* A. E. Clayton: "Third Harmonics in the Phase Pressure of Cylindrical-Field Alternators," *Electrician*, 1916, vol. 77, p. 216.

† Assuming that even harmonics are not present in the current wave. If even harmonics are present, for dealing with these harmonics $M$ must be an odd number if $N$ is odd. If $N$ is even, and full-pitch coils are used, the resulting M.M.F. due to even harmonics in the current is nil for a balanced polyphase system.

‡ The unusual case of one slot per pole per phase is an exception.

Thus all odd current harmonics of the third order give rise to purely alternating M.M.F.'s corresponding to odd multiples of three times the main number of poles for all normal three-phase and six-phase windings, excepting only the case mentioned above. With a nine-phase winding, the ninth current harmonic will give rise to an alternating field of nine times the main number of poles if the winding is of the single-layer type; for a two-layer winding as used in synchronous converters the effect of the ninth current harmonic will be zero.

In general it may be stated that, in every case of a two-layer winding, purely alternating M.M.F. components can only be produced when $N$ is an odd multiple of 2.

TABLE 9.

*The M.M.F. Components Established by Current Harmonics of Various Orders.*

The data relate to full-pitch coils and to polyphase windings.

| Number of phases of winding, $N$ = | M.M.F. component due to current harmonic of order | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 3 | | 5 | | 7 | | 9 | | 11 | | 2 | |
| | ↶ | ↷ | ↶ | ↷ | ↶ | ↷ | ↶ | ↷ | ↶ | ↷ | ↶ | ↷ | ↶ | ↷ |
| 3 | 1<br>7<br>13<br>etc. | 5<br>11<br>17<br>etc. | 3<br>9<br>15<br>etc. | 3<br>9<br>15<br>etc. | 5<br>11<br>17<br>etc. | 1<br>7<br>13<br>etc. | 1<br>7<br>13<br>etc. | 5<br>11<br>17<br>etc. | 3<br>9<br>15<br>etc. | 3<br>9<br>15<br>etc. | 5<br>11<br>17<br>etc. | 1<br>7<br>13<br>etc. | 5<br>11<br>17<br>etc. | 1<br>7<br>13<br>etc. |
| 4 | 1<br>5<br>9<br>etc. | 3<br>7<br>11<br>etc. | 3<br>7<br>11<br>etc. | 1<br>5<br>9<br>etc. | 1<br>5<br>9<br>etc. | 3<br>7<br>11<br>etc. | 3<br>7<br>11<br>etc. | 1<br>5<br>9<br>etc. | 1<br>5<br>9<br>etc. | 3<br>7<br>11<br>etc. | 3<br>7<br>11<br>etc. | 1<br>5<br>9<br>etc. | nil<br>nil<br>nil | nil<br>nil<br>nil |
| 5 | 1<br>11<br>21<br>etc. | 9<br>19<br>29<br>etc. | 3<br>13<br>23<br>etc. | 7<br>17<br>27<br>etc. | 5<br>15<br>25<br>etc. | 5<br>15<br>25<br>etc. | 7<br>17<br>27<br>etc. | 3<br>13<br>23<br>etc. | 9<br>19<br>29<br>etc. | 1<br>11<br>21<br>etc. | 1<br>11<br>21<br>etc. | 9<br>19<br>29<br>etc. | 7<br>17<br>27<br>etc. | 3<br>13<br>23<br>etc. |
| 6 | 1<br>7<br>13<br>etc. | 5<br>11<br>17<br>etc. | 3<br>9<br>15<br>etc. | 3<br>9<br>15<br>etc. | 5<br>11<br>17<br>etc. | 1<br>7<br>13<br>etc. | 1<br>7<br>13<br>etc. | 5<br>11<br>17<br>etc. | 3<br>9<br>15<br>etc. | 3<br>9<br>15<br>etc. | 5<br>11<br>17<br>etc. | 1<br>7<br>13<br>etc. | nil<br>nil<br>nil | nil<br>nil<br>nil |
| 8 | 1<br>9<br>17<br>etc. | 7<br>15<br>23<br>etc. | 3<br>11<br>19<br>etc. | 5<br>13<br>21<br>etc. | 5<br>13<br>21<br>etc. | 3<br>11<br>19<br>etc. | 7<br>15<br>23<br>etc. | 1<br>9<br>17<br>etc. | 1<br>9<br>17<br>etc. | 7<br>15<br>23<br>etc. | 3<br>11<br>19<br>etc. | 5<br>13<br>21<br>etc. | nil<br>nil<br>nil | nil<br>nil<br>nil |
| 9 | 1<br>19<br>37<br>etc. | 17<br>35<br>53<br>etc. | 3<br>21<br>39<br>etc. | 15<br>33<br>51<br>etc. | 5<br>23<br>41<br>etc. | 13<br>31<br>49<br>etc. | 7<br>25<br>43<br>etc. | 11<br>29<br>47<br>etc. | 9<br>27<br>45<br>etc. | 9<br>27<br>45<br>etc. | 11<br>29<br>47<br>etc. | 7<br>25<br>43<br>etc. | 11<br>29<br>47<br>etc. | 7<br>25<br>43<br>etc. |
| 12 | 1<br>13<br>25<br>etc. | 11<br>23<br>35<br>etc. | 3<br>15<br>27<br>etc. | 9<br>21<br>33<br>etc. | 5<br>17<br>29<br>etc. | 7<br>19<br>31<br>etc. | 7<br>19<br>31<br>etc. | 5<br>17<br>29<br>etc. | 9<br>21<br>33<br>etc. | 3<br>15<br>27<br>etc. | 11<br>23<br>35<br>etc. | 1<br>13<br>25<br>etc. | nil<br>nil<br>nil | nil<br>nil<br>nil |

When the order of the current harmonic is such that $n = MN \pm 1$, the M.M.F. due to the harmonic has a distribution corresponding exactly to that due to the fundamental current harmonic. The angular speed of the resulting M.M.F. is, however, $MN \pm 1$ times that for the fundamental current harmonic. In cases where $n = MN + 1$ the corresponding M.M.F. rotates in the same direction as that when $n = 1$; but when $n = MN - 1$ the motion is in the reverse direction.

It will be noticed that for the most common cases of $N = 3$, 4 or 6 all the current harmonics fall into one of the above groups, i.e. $n = MN \pm 1$ or $n = (2M - 1)N$ if $N$ is odd, or $(2M - 1)N/2$ if $N$ is an odd multiple of 2.

For larger values of $N$ such as are met with occasionally, e.g. $N = 9$ or $N = 12$, the majority of the current harmonics will give rise to M.M.F. waves of entirely different shapes from those due to the fundamental, and, moreover, will not contain any terms corresponding to the main number of poles.

Even when $N = 5$, no fundamental field component is produced by the 3rd, 5th or 7th harmonics in the current wave. When $N = 9$ only the fundamental and the 17th and 19th current harmonics (out of the first 20 orders) give rise to an M.M.F. component having the main number of poles.

The effect of current harmonics of orders $MN \pm 1$ is of especial interest since the effect of the variations of the magnetomotive force of an alternating-current synchronous machine will tend ultimately to establish current harmonics of corresponding orders.*

Amongst others, these current harmonics will give rise to an M.M.F. component having a number of poles equal to $n$ times the main number rotating in a positive direction at exactly the same speed (revolutions per second) as the main component of the total M.M.F. As a result, when the current is not sinusoidal, and under the conditions assumed, the constant, synchronously rotating component of the resulting M.M.F. is no longer of sinusoidal field form. That is, if such a machine were provided with perfect amortisseurs so as to eliminate completely the fluctuations in the armature M.M.F., the wave-form of the resulting armature M.M.F. would not be sinusoidal but would contain harmonics of orders corresponding to the harmonics present in the current wave.

## CONCLUSION.

A mathematical development of the theory of the magnetomotive force developed by armature windings, on the lines of that here given, lends itself readily to dealing with abnormal cases, such as, for example, any case in which the symmetry of the winding is advertently or inadvertently disturbed. The winding factors plotted in the present paper, and tabulated in an Appendix, may also be applied to E.M.F. calculations. For such calculations, however, the slot-width factors, $f_{sp}$, do not apply, as it may be taken that there is no appreciable phase difference in the E.M.F. induced in the conductors on the two walls of the slot.

In the preparation of the manuscript of the paper, and in the construction of the diagrams, the author has received valued help from Mr. J. Walton, Associate of the Manchester College of Technology, and would like to record his thanks for and appreciation of that assistance. The author is also indebted to Mr. H. J. Shelley, B.Sc., for assistance in reading the proofs of the paper.

## APPENDIX.

### (1) THE FOURIER SERIES FOR THE WAVE-FORM SHOWN IN FIG. 2.

For all the terms except those of the zero-th order, the analysis is not affected by displacing the wave bodily relative to the axis.

With the origin taken to be $\pi/2$ radians from the axis of the coil, the amplitude of the $p$th sine term is given by :—

$$\begin{aligned} A_p &= \frac{1}{\pi}\int_0^{2\pi} y \sin p\theta_1 d\theta_1 \\ &= \frac{X}{\pi}\int_\delta^{\pi-\delta} \sin p\theta_1 d\theta_1 \\ &= \frac{X}{\pi}\Big\{\cos p\delta - \cos p(\pi - \delta)\Big\} \\ &= \frac{2X}{\pi}\cos p\delta \\ &= \frac{2X}{\pi}\sin\frac{p\pi}{2} \times \sin p\alpha \end{aligned}$$

if $p$ is an odd number,

and $= 0$ if $p$ is an even number.

Similarly, the amplitude of the $p$th cosine term is :—

$$\begin{aligned} B_p &= \frac{X}{\pi}\int_\delta^{\pi-\delta} \cos p\theta_1 d\theta_1 \\ &= \frac{X}{\pi}\Big\{\sin p(\pi - \delta) - \sin p\delta\Big\} \\ &= -\frac{2X}{\pi}\sin p\delta \\ &= \frac{2X}{\pi}\cos\frac{p\pi}{2} \times \sin p\alpha \end{aligned}$$

if $p$ is an even number,

and $= 0$ if $p$ is an odd number.

With the origin taken at the axis of the coil, the amplitude of the $p$th cosine term becomes :—

$$\begin{aligned} B_p &= \frac{X}{\pi}\left[\int_0^{\alpha} \cos p\theta d\theta + \int_{2\pi-\alpha}^{2\pi} \cos p\theta d\theta\right] \\ &= \frac{X}{\pi}\Big\{\sin p\alpha - \sin p(2\pi - \alpha)\Big\} \\ &= \frac{2X}{\pi}\sin p\alpha \end{aligned}$$

and the amplitude of the $p$th sine term is :—

$$A_p = \frac{X}{\pi}\Big\{\cos p(2\pi - \alpha) - \cos p\alpha\Big\} = 0$$

---

* A. E. CLAYTON: *Journal I.E.E.*, 1916, vol. 54, p. 103.

### (2) Winding Factors for Uniformly Distributed Windings.*

| Spread, in elect. degrees | $\frac{\sin p\beta}{p\beta}$ | Spread, in elect. degrees | $\frac{\sin p\beta}{p\beta}$ | Spread, in elect. degrees | $\frac{\sin p\beta}{p\beta}$ | Spread, in elect. degrees | $\frac{\sin p\beta}{p\beta}$ |
|---|---|---|---|---|---|---|---|
| 0 | 1·000 | 140 | 0·769 | 280 | 0·263 | 660 | −0·087 |
| 2 | 1·000 | 142 | 0·763 | 282 | 0·256 | 670 | −0·072 |
| 4 | 1·000 | 144 | 0·757 | 284 | 0·248 | 680 | −0·059 |
| 6 | 1·000 | 146 | 0·751 | 286 | 0·241 | 690 | −0·043 |
| 8 | 0·999 | 148 | 0·744 | 288 | 0·234 | 700 | −0·028 |
| 10 | 0·999 | 150 | 0·738 | 290 | 0·227 | 710 | −0·014 |
| 12 | 0·998 | 152 | 0·732 | 292 | 0·220 | 720 | 0 |
| 14 | 0·998 | 154 | 0·725 | 294 | 0·212 | 740 | 0·027 |
| 16 | 0·997 | 156 | 0·719 | 296 | 0·205 | 760 | 0·052 |
| 18 | 0·996 | 158 | 0·712 | 298 | 0·198 | 780 | 0·073 |
| 20 | 0·995 | 160 | 0·705 | 300 | 0·191 | 800 | 0·092 |
| 22 | 0·994 | 162 | 0·699 | 302 | 0·184 | 820 | 0·107 |
| 24 | 0·993 | 164 | 0·692 | 304 | 0·177 | 840 | 0·118 |
| 26 | 0·991 | 166 | 0·685 | 306 | 0·170 | 860 | 0·125 |
| 28 | 0·990 | 168 | 0·678 | 308 | 0·163 | 880 | 0·128 |
| 30 | 0·988 | 170 | 0·672 | 310 | 0·156 | 900 | 0·127 |
| 32 | 0·987 | 172 | 0·665 | 312 | 0·149 | 920 | 0·123 |
| 34 | 0·985 | 174 | 0·658 | 314 | 0·143 | 940 | 0·115 |
| 36 | 0·984 | 176 | 0·651 | 316 | 0·136 | 960 | 0·103 |
| 38 | 0·982 | 178 | 0·644 | 318 | 0·129 | 980 | 0·090 |
| 40 | 0·980 | 180 | 0·637 | 320 | 0·122 | 1 000 | 0·073 |
| 42 | 0·978 | 182 | 0·630 | 322 | 0·116 | 1 020 | 0·056 |
| 44 | 0·976 | 184 | 0·622 | 324 | 0·109 | 1 040 | 0·038 |
| 46 | 0·973 | 186 | 0·615 | 326 | 0·103 | 1 060 | 0·019 |
| 48 | 0·971 | 188 | 0·608 | 328 | 0·096 | 1 080 | 0 |
| 50 | 0·968 | 190 | 0·601 | 330 | 0·090 | 1 100 | −0·017 |
| 52 | 0·966 | 192 | 0·594 | 332 | 0·084 | 1 120 | −0·035 |
| 54 | 0·963 | 194 | 0·586 | 334 | 0·077 | 1 140 | −0·050 |
| 56 | 0·961 | 196 | 0·578 | 336 | 0·071 | 1 160 | −0·064 |
| 58 | 0·958 | 198 | 0·572 | 338 | 0·065 | 1 180 | −0·075 |
| 60 | 0·955 | 200 | 0·564 | 340 | 0·059 | 1 200 | −0·083 |
| 62 | 0·952 | 202 | 0·557 | 342 | 0·052 | 1 220 | −0·088 |
| 64 | 0·949 | 204 | 0·550 | 344 | 0·046 | 1 240 | −0·091 |
| 66 | 0·946 | 206 | 0·542 | 346 | 0·040 | 1 260 | −0·091 |
| 68 | 0·942 | 208 | 0·534 | 348 | 0·034 | 1 280 | −0·088 |
| 70 | 0·939 | 210 | 0·527 | 350 | 0·029 | 1 300 | −0·083 |
| 72 | 0·935 | 212 | 0·520 | 352 | 0·023 | 1 320 | −0·075 |
| 74 | 0·932 | 214 | 0·512 | 354 | 0·017 | 1 340 | −0·066 |
| 76 | 0·928 | 216 | 0·505 | 356 | 0·011 | 1 360 | −0·054 |
| 78 | 0·924 | 218 | 0·497 | 358 | 0·006 | 1 380 | −0·042 |
| 80 | 0·920 | 220 | 0·489 | 360 | 0 | 1 400 | −0·028 |
| 82 | 0·917 | 222 | 0·482 | 370 | −0·027 | 1 420 | −0·014 |
| 84 | 0·913 | 224 | 0·474 | 380 | −0·052 | 1 440 | 0 |
| 86 | 0·909 | 226 | 0·467 | 390 | −0·076 | 1 460 | 0·014 |
| 88 | 0·904 | 228 | 0·459 | 400 | −0·098 | 1 480 | 0·027 |
| 90 | 0·900 | 230 | 0·451 | 410 | −0·118 | 1 500 | 0·038 |
| 92 | 0·896 | 232 | 0·444 | 420 | −0·136 | 1 520 | 0·049 |
| 94 | 0·892 | 234 | 0·436 | 430 | −0·153 | 1 540 | 0·057 |
| 96 | 0·887 | 236 | 0·429 | 440 | −0·167 | 1 560 | 0·063 |
| 98 | 0·882 | 238 | 0·421 | 450 | −0·180 | 1 580 | 0·068 |
| 100 | 0·878 | 240 | 0·414 | 460 | −0·191 | 1 600 | 0·071 |
| 102 | 0·873 | 242 | 0·406 | 470 | −0·200 | 1 620 | 0·071 |
| 104 | 0·868 | 244 | 0·398 | 480 | −0·207 | 1 640 | 0·069 |
| 106 | 0·863 | 246 | 0·391 | 490 | −0·212 | 1 660 | 0·065 |
| 108 | 0·858 | 248 | 0·383 | 500 | −0·215 | 1 680 | 0·059 |
| 110 | 0·853 | 250 | 0·375 | 510 | −0·217 | 1 700 | 0·052 |
| 112 | 0·848 | 252 | 0·368 | 520 | −0·217 | 1 720 | 0·043 |
| 114 | 0·843 | 254 | 0·360 | 530 | −0·215 | 1 740 | 0·033 |
| 116 | 0·838 | 256 | 0·353 | 540 | −0·212 | 1 760 | 0·029 |
| 118 | 0·832 | 258 | 0·345 | 550 | −0·208 | 1 780 | 0·011 |
| 120 | 0·827 | 260 | 0·338 | 560 | −0·202 | 1 800 | 0 |
| 122 | 0·822 | 262 | 0·330 | 570 | −0·194 | 1 820 | −0·011 |
| 124 | 0·816 | 264 | 0·323 | 580 | −0·186 | 1 840 | −0·021 |
| 126 | 0·810 | 266 | 0·315 | 590 | −0·176 | 1 860 | −0·031 |
| 128 | 0·805 | 268 | 0·308 | 600 | −0·165 | 1 880 | −0·039 |
| 130 | 0·799 | 270 | 0·300 | 610 | −0·154 | 1 900 | −0·046 |
| 132 | 0·793 | 272 | 0·293 | 620 | −0·142 | 1 920 | −0·052 |
| 134 | 0·787 | 274 | 0·285 | 630 | −0·129 | 1 940 | −0·056 |
| 136 | 0·781 | 276 | 0·278 | 640 | −0·115 | 1 960 | −0·058 |
| 138 | 0·775 | 278 | 0·270 | 650 | −0·101 | 1 980 | −0·058 |
|  |  |  |  |  |  | 2 000 | −0·056 |
|  |  |  |  |  |  | 2 020 | −0·053 |
|  |  |  |  |  |  | 2 040 | −0·049 |
|  |  |  |  |  |  | 2 060 | −0·043 |
|  |  |  |  |  |  | 2 080 | −0·035 |
|  |  |  |  |  |  | 2 100 | −0·027 |
|  |  |  |  |  |  | 2 120 | −0·019 |
|  |  |  |  |  |  | 2 140 | −0·009 |
|  |  |  |  |  |  | 2 160 | 0 |

* These factors may also be utilized for slot-width factors.

### (3) Table of Winding Factors.

$$f_{wp} = \frac{\sin sp\gamma}{s \sin p\gamma}$$

| Equiv. slot-pitch, in elec. degrees | Number of slots per coil-side, s = |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 12 |
| 2 | 1·000 | 1·000 | 0·999 | 0·999 | 0·998 | 0·997 | 0·995 | 0·993 |
| 4 | 0·999 | 0·998 | 0·997 | 0·995 | 0·993 | 0·990 | 0·980 | 0·971 |
| 6 | 0·999 | 0·996 | 0·993 | 0·989 | 0·984 | 0·972 | 0·955 | 0·935 |
| 8 | 0·998 | 0·994 | 0·988 | 0·980 | 0·972 | 0·949 | 0·921 | 0·888 |
| 10 | 0·996 | 0·990 | 0·981 | 0·969 | 0·956 | 0·919 | 0·879 | 0·828 |
| 12 | 0·995 | 0·986 | 0·973 | 0·957 | 0·937 | 0·889 | 0·829 | 0·754 |
| 14 | 0·993 | 0·980 | 0·963 | 0·941 | 0·915 | 0·850 | 0·771 | 0·680 |
| 16 | 0·990 | 0·974 | 0·952 | 0·924 | 0·890 | 0·807 | 0·708 | 0·596 |
| 18 | 0·988 | 0·967 | 0·939 | 0·904 | 0·863 | 0·760 | 0·639 | 0·507 |
| 20 | 0·985 | 0·960 | 0·927 | 0·882 | 0·832 | 0·709 | 0·567 | 0·417 |
| 22 | 0·982 | 0·951 | 0·910 | 0·859 | 0·798 | 0·655 | 0·492 | 0·325 |
| 24 | 0·978 | 0·942 | 0·894 | 0·833 | 0·762 | 0·598 | 0·417 | 0·236 |
| 26 | 0·974 | 0·933 | 0·876 | 0·806 | 0·725 | 0·540 | 0·341 | 0·151 |
| 28 | 0·970 | 0·922 | 0·857 | 0·777 | 0·685 | 0·478 | 0·266 | 0·072 |
| 30 | 0·966 | 0·911 | 0·837 | 0·746 | 0·641 | 0·418 | 0·193 | 0 |
| 32 | 0·961 | 0·899 | 0·815 | 0·715 | 0·601 | 0·357 | 0·124 | −0·063 |
| 34 | 0·956 | 0·886 | 0·793 | 0·682 | 0·558 | 0·297 | 0·059 | −0·116 |
| 36 | 0·951 | 0·873 | 0·770 | 0·647 | 0·513 | 0·238 | 0 | −0·159 |
| 38 | 0·946 | 0·859 | 0·745 | 0·612 | 0·468 | 0·180 | −0·053 | −0·190 |
| 40 | 0·940 | 0·844 | 0·720 | 0·576 | 0·422 | 0·125 | −0·100 | −0·211 |
| 42 | 0·934 | 0·829 | 0·694 | 0·539 | 0·376 | 0·073 | −0·140 | −0·221 |
| 44 | 0·927 | 0·813 | 0·667 | 0·502 | 0·331 | 0·023 | −0·172 | −0·221 |
| 46 | 0·921 | 0·796 | 0·639 | 0·464 | 0·285 | −0·020 | −0·196 | −0·212 |
| 48 | 0·914 | 0·779 | 0·611 | 0·426 | 0·241 | −0·064 | −0·213 | −0·195 |
| 50 | 0·906 | 0·762 | 0·583 | 0·388 | 0·197 | −0·101 | −0·222 | −0·171 |
| 52 | 0·899 | 0·744 | 0·553 | 0·350 | 0·155 | −0·133 | −0·225 | −0·141 |
| 54 | 0·891 | 0·725 | 0·524 | 0·310 | 0·113 | −0·162 | −0·220 | −0·108 |
| 56 | 0·883 | 0·706 | 0·494 | 0·274 | 0·074 | −0·185 | −0·210 | −0·072 |
| 58 | 0·875 | 0·687 | 0·464 | 0·237 | 0·036 | −0·203 | −0·194 | −0·036 |
| 60 | 0·866 | 0·667 | 0·433 | 0·200 | 0 | −0·217 | −0·173 | 0 |
| 62 | 0·857 | 0·646 | 0·402 | 0·164 | −0·034 | −0·225 | −0·149 | 0·034 |
| 64 | 0·848 | 0·626 | 0·372 | 0·139 | −0·065 | −0·228 | −0·121 | 0·064 |
| 66 | 0·839 | 0·605 | 0·341 | 0·094 | −0·092 | −0·228 | −0·092 | 0·090 |
| 68 | 0·829 | 0·583 | 0·311 | 0·062 | −0·121 | −0·223 | −0·061 | 0·111 |
| 70 | 0·819 | 0·561 | 0·280 | 0·030 | −0·145 | −0·215 | −0·030 | 0·126 |
| 72 | 0·809 | 0·539 | 0·250 | 0 | −0·167 | −0·202 | 0 | 0·135 |
| 74 | 0·799 | 0·517 | 0·220 | −0·029 | −0·185 | −0·187 | 0·029 | 0·138 |
| 76 | 0·788 | 0·495 | 0·191 | −0·056 | −0·201 | −0·168 | 0·056 | 0·135 |
| 78 | 0·777 | 0·472 | 0·162 | −0·082 | −0·214 | −0·173 | 0·079 | 0·126 |
| 80 | 0·766 | 0·449 | 0·133 | −0·106 | −0·225 | −0·125 | 0·100 | 0·112 |
| 82 | 0·755 | 0·426 | 0·105 | −0·129 | −0·232 | −0·101 | 0·117 | 0·094 |
| 84 | 0·743 | 0·403 | 0·078 | −0·149 | −0·237 | −0·076 | 0·129 | 0·073 |
| 86 | 0·731 | 0·380 | 0·051 | −0·168 | −0·239 | −0·051 | 0·138 | 0·050 |
| 88 | 0·719 | 0·357 | 0·025 | −0·185 | −0·240 | −0·025 | 0·142 | 0·025 |
| 90 | 0·707 | 0·333 | 0 | −0·200 | −0·236 | 0 | 0·141 | 0 |
| 92 | 0·695 | 0·310 | −0·024 | −0·213 | −0·230 | 0·024 | 0·137 | −0·024 |
| 94 | 0·682 | 0·287 | −0·048 | −0·224 | −0·223 | 0·047 | 0·129 | −0·045 |
| 96 | 0·669 | 0·264 | −0·070 | −0·233 | −0·213 | 0·068 | 0·117 | −0·066 |
| 98 | 0·656 | 0·241 | −0·091 | −0·242 | −0·202 | 0·088 | 0·102 | −0·082 |
| 100 | 0·643 | 0·218 | −0·112 | −0·245 | −0·189 | 0·105 | 0·084 | −0·094 |
| 102 | 0·629 | 0·195 | −0·131 | −0·249 | −0·174 | 0·120 | 0·064 | −0·102 |
| 104 | 0·616 | 0·172 | −0·149 | −0·250 | −0·157 | 0·132 | 0·043 | −0·105 |
| 106 | 0·602 | 0·150 | −0·166 | −0·250 | −0·140 | 0·141 | 0·022 | −0·104 |
| 108 | 0·588 | 0·127 | −0·182 | −0·247 | −0·121 | 0·147 | 0 | −0·098 |
| 110 | 0·574 | 0·105 | −0·196 | −0·243 | −0·102 | 0·150 | −0·021 | −0·088 |
| 112 | 0·559 | 0·084 | −0·210 | −0·238 | −0·082 | 0·151 | −0·041 | −0·075 |
| 114 | 0·545 | 0·062 | −0·222 | −0·230 | −0·061 | 0·148 | −0·060 | −0·058 |
| 116 | 0·530 | 0·041 | −0·232 | −0·222 | −0·041 | 0·143 | −0·076 | −0·040 |
| 118 | 0·515 | 0·020 | −0·242 | −0·211 | −0·020 | 0·135 | −0·089 | −0·020 |
| 120 | 0·500 | 0 | −0·250 | −0·200 | 0 | 0·125 | −0·100 | 0 |
| 122 | 0·485 | −0·020 | −0·257 | −0·187 | 0·020 | 0·113 | −0·107 | 0·020 |
| 124 | 0·469 | −0·039 | −0·263 | −0·174 | 0·039 | 0·099 | −0·112 | 0·038 |
| 126 | 0·454 | −0·058 | −0·267 | −0·159 | 0·058 | 0·082 | −0·112 | 0·053 |
| 128 | 0·438 | −0·077 | −0·270 | −0·143 | 0·075 | 0·065 | −0·110 | 0·069 |
| 130 | 0·423 | −0·095 | −0·272 | −0·126 | 0·092 | 0·046 | −0·104 | 0·079 |
| 132 | 0·407 | −0·113 | −0·272 | −0·109 | 0·107 | 0·028 | −0·095 | 0·087 |
| 134 | 0·391 | −0·130 | −0·272 | −0·092 | 0·121 | 0·009 | −0·083 | 0·090 |
| 136 | 0·375 | −0·146 | −0·270 | −0·074 | 0·133 | −0·009 | −0·069 | 0·089 |
| 138 | 0·358 | −0·162 | −0·266 | −0·055 | 0·144 | −0·028 | −0·054 | 0·085 |
| 140 | 0·342 | −0·177 | −0·262 | −0·037 | 0·154 | −0·046 | −0·036 | 0·077 |
| 142 | 0·326 | −0·192 | −0·257 | −0·018 | 0·161 | −0·062 | −0·018 | 0·065 |
| 144 | 0·309 | −0·206 | −0·250 | 0 | 0·167 | −0·076 | 0 | 0·051 |
| 146 | 0·292 | −0·219 | −0·242 | 0·018 | 0·171 | −0·090 | 0·018 | 0·035 |
| 148 | 0·276 | −0·232 | −0·234 | 0·036 | 0·172 | −0·102 | 0·036 | 0·018 |
| 150 | 0·259 | −0·244 | −0·224 | 0·054 | 0·172 | −0·112 | 0·052 | 0 |
| 152 | 0·242 | −0·255 | −0·214 | 0·070 | 0·171 | −0·119 | 0·066 | −0·018 |
| 154 | 0·225 | −0·266 | −0·202 | 0·087 | 0·167 | −0·124 | 0·079 | −0·035 |
| 156 | 0·208 | −0·276 | −0·190 | 0·102 | 0·162 | −0·127 | 0·089 | −0·050 |
| 158 | 0·191 | −0·285 | −0·177 | 0·117 | 0·155 | −0·127 | 0·096 | −0·063 |
| 160 | 0·174 | −0·293 | −0·163 | 0·130 | 0·147 | −0·125 | 0·100 | −0·073 |
| 162 | 0·156 | −0·301 | −0·149 | 0·142 | 0·137 | −0·120 | 0·101 | −0·080 |
| 164 | 0·139 | −0·307 | −0·134 | 0·155 | 0·125 | −0·113 | 0·099 | −0·084 |
| 166 | 0·122 | −0·313 | −0·118 | 0·165 | 0·112 | −0·101 | 0·095 | −0·084 |
| 168 | 0·105 | −0·319 | −0·102 | 0·174 | 0·099 | −0·093 | 0·087 | −0·080 |
| 170 | 0·087 | −0·323 | −0·085 | 0·182 | 0·084 | −0·081 | 0·077 | −0·074 |
| 172 | 0·070 | −0·327 | −0·069 | 0·188 | 0·068 | −0·067 | 0·064 | −0·062 |
| 174 | 0·052 | −0·330 | −0·052 | 0·193 | 0·052 | −0·051 | 0·050 | −0·049 |
| 176 | 0·035 | −0·332 | −0·035 | 0·197 | 0·035 | −0·034 | 0·034 | −0·034 |
| 178 | 0·017 | −0·333 | −0·017 | 0·199 | 0·017 | −0·017 | 0·017 | −0·017 |
| 180 | 0 | −0·333 | −0·000 | 0·200 | 0 | 0 | 0 | 0 |

### (4) THE FOURIER SERIES FOR THE WAVE-FORM SHOWN IN FIG. 6.

Taking the origin at the axis of the coil, the amplitude of the $p$th cosine term becomes :—

$$
\begin{aligned}
B_p &= \frac{1}{\pi}\int_0^{2\pi} y \cos p\theta d\theta \\
&= \frac{2}{\pi}\left\{ \int_0^{\alpha+\beta} X \cos p\theta d\theta - \int_{\alpha+\beta}^{\alpha-\beta} \frac{X}{2\beta}(\theta - \overline{\alpha - \beta}) \cos p\theta d\theta \right\} \\
&= \frac{2X}{\pi}\left\{ \left[ \frac{1}{p} \sin p\theta \right]_0^{\alpha+\beta} \right. \\
&\quad \left. - \frac{1}{2\beta}\left[ \frac{1}{p^2}\cos p\theta + \frac{1}{p}\theta \sin p\theta - \frac{\alpha-\beta}{p} \sin p\theta \right]_{\alpha-\beta}^{\alpha+\beta} \right\} \\
&= \frac{2X}{\pi} \times \frac{1}{2\beta} \times \frac{1}{p^2}\left\{ \cos p(\alpha - \beta) - \cos p(\alpha + \beta) \right\} \\
&= \frac{2X}{\pi} \times \frac{\sin p\beta}{p\beta} \times \frac{1}{p} \sin p\alpha
\end{aligned}
$$

In a similar manner, or indeed by mere inspection of the wave, it may be shown that sine terms are absent.

### (5) THE TOTAL M.M.F. DUE TO A CONCENTRIC COIL (cf. FIG. 8).

Taking $X/s$ to be the value of the M.M.F. developed by each component slot-coil, the total amplitude of the $p$th harmonic becomes :—

$$
\begin{aligned}
&\frac{2X}{\pi s}\left\{ \sin p\alpha_0 + \sin p(\alpha_0 + 2\gamma) + \ldots + \sin p(\alpha_0 + \overline{s-1}\,2\gamma) \right\} \\
&\qquad = \frac{2X}{\pi s} \times \frac{\sin sp\gamma}{\sin p\gamma} \times \sin p(\alpha_0 + \overline{s - 1}\gamma) \\
&\qquad = \frac{2X}{\pi} \times \frac{\sin sp\gamma}{s \sin p\gamma} \times \sin p\alpha
\end{aligned}
$$

where $\alpha = \alpha_0 + (s - 1)\gamma =$ the mean span of the coil.

# ADDRESS TO THE LONDON STUDENTS' SECTION

By F. GILL, President.

(*Address delivered 9th March,* 1923.)

## ECONOMICS IN ENGINEERING.

In my presidential address * to the Institution I made use of the following words:—

"I do not remember an instance of a student being familiar with the economic aspect of engineering studies, nor of one who had any idea of how to tackle a problem of engineering economics. Yet that question of economics is the fundamental problem of the engineer."

Accordingly it seemed incumbent on me to talk to you mainly about this matter, since if it is so important, and if it is not being generally treated in the schools, I must do what I can to ventilate the subject. I have spoken on this line of thought to several of the Local Centres, but have not so far been challenged as to the accuracy of the statement that students do not appear to be taught this matter, though it is not to be expected that the statement is universally true. Frederic Bacon, Professor of Engineering at University College, Swansea, has recently stated †:—

"During and since the War, labour and economic troubles have been so acute that it is incredible that our educational system for training engineers can much longer blink the fact that engineering is not merely concerned with materials and design; but with finance, economics, labour, materials and design."

So that it may perhaps be accepted that the accusation is in fact sufficiently accurate.

Engineering is in reality a three-dimensional work since it involves considerations arising out of the physical properties of materials, the economic problem and the psychology of those doing the work, and these three of necessity react on each other. But the one to be referred to now is the economic problem.

What do we mean by economy and economics? Originally the word referred to the management of the household by a frugal use of money; we may say it differs from parsimony, which implies an improper saving of expense. Until recently it seems not unfair to say that it was concerned solely with the subject known as Political Economy, which has been defined in Professor Marshall's "Principles of Economics" as "a study of man's actions in the ordinary business of life; it inquires how he gets his income and how he spends it." The engineer, however, has given a new meaning to the word (though, of course, it is part of the larger subject), since he has applied its processes to help him in selecting plant and methods for achieving what he wants to do.

The engineer's job is not only applied physics; it is that, of course, but it is more, for that by itself would neglect the important element of cost. There are three very important sections to his work, namely:—

*Requirements*, in which he sets out as exactly as is practicable just what is to be done and the limits of accuracy to be observed. This is important, because it is the absence of strict requirements which so often permits unlike things to be quoted as alternatives.

*Design*, in which he arrives at alternative methods of filling the requirements.

*Selection*, in which he chooses which of the alternative designs (each of which will meet the requirements) it is best to employ. For how often it happens that, when a piece of work has been constructed according to the engineers' designs, the management can only operate on a margin, important no doubt, but the question as to whether or not the work shall be profit-earning has been settled when the design was made. For consider, it is settled, always within margins, what shall be the money payable as a return on the capital employed; the money required to offset wear and tear and obsolescence; the money required for maintenance; the cost of feeding the plant and the cost of such matters as insurance, taxes and overhead charges. It is almost impossible for efficient management to make profit out of a poor engineering job.

If this is so, then the engineer is vitally concerned with the profit made by his firm and he cannot stand aloof as one connected only with the scientific and mechanical sides of the business; he is, and must regard himself as being, very much concerned with the question of profit earning.

So we see that one important part of the engineer's work is selection from among alternatives, any of which will achieve the result desired. This part of his work may, in fact, be illustrated by Fig. 1. This curve shows a number of alternatives, $N$, *any one of which gives the same desired requirements*, plotted against the cost. There is invariably a bottom point to the curve and the engineer is always seeking that point as it shows him how to do his work at least cost.

Now what do we mean by least cost? Let us get right back to the origin so as not to be misled by the names of tokens, for though it is convenient to consider cost in terms of money, yet really money is only a token. When man works he produces something—let us assume he grows and harvests potatoes. If he is diligent and thrifty he does not consume all the potatoes he produces, and the spare potatoes are his capital. Because he has these spare, other men are anxious to work for him, to grow corn to exchange for his potatoes, for example. In fact, directly he consumes less than he produces he becomes a capitalist able to call on others for their work. The capitalist is wanted, and not to become one indicates an unthrifty spirit.

---

* See *Journal I.E.E.*, 1922, vol. 61, p. 1.

† "The Importance of Economics," *Western Mail*, 23 February, 1923.

Since it is inconvenient to trade by barter, that is exchange of goods, money, the common denominator which goes into all things commercial, was invented, and, still later, credit, which in large transactions replaces money. But at the back of all the complex matter of trade, cost involves the expenditure of human effort and so the effort to do a thing at lowest cost means with the least expenditure of human effort.

For example, to produce a motor at lower cost involves less effort in producing the motor and more purchasers to enjoy the benefit of the machine and so the lightening of their labours. Like mercy, "it blesses him that gives and him that takes" and, rightly considered, is work in which any man, even though he be an idealist, may take a pride and delight, always supposing, of course, that the work itself is beneficial to humanity.

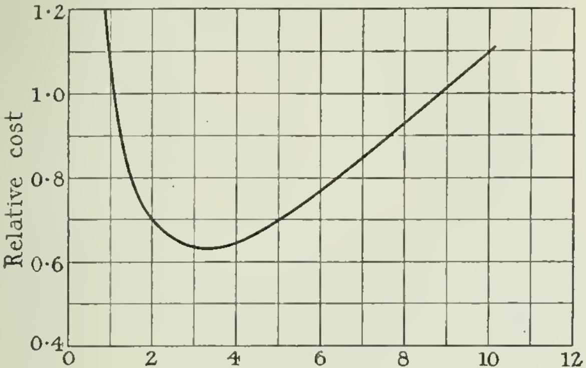


FIG. 1.

Just here a caution is necessary. In Fig. 1 we saw that at the bottom of the curve the rate of change in slope is very small, that not much was gained if in that case $N$ varied between 2·5 and 4, and that it would be waste effort to push the search for least cost to its ultimate conclusion. So we get as a requirement in the engineer the sense of the proportion of things—he must know when to stop.

Fig. 2 illustrates this; obviously it may not be economical to push the quest for efficiency to the last, seeing that in the illustration the cost of obtaining additional efficiency becomes so burdensome.

If in this figure we read on the right-hand scale "Return, in £" instead of "Efficiency, per cent," then it is seen that for the expenditure of the first £1 in cost we get an increased return of £8; for the next £1 we get a return of £4; then £2, then £1, then £0·5 and so on. But at the third £ cost we reach the point where an additional cost of £1 will return only £1, and after that the return will be less than the cost. This curve illustrates the law known as that of Diminishing Returns and the point of Negative Return.

We come then to this: the engineer's job is the wise utilization of money, and in achieving this he has to take many things into consideration.

Assume that a reservoir is to be made and a dam constructed at the end of a valley; theoretically, given enough labour and material, anybody can do this; it is only necessary to heap in sufficient of the right kind of material, and the job is simple enough. But to build the dam rightly at the lowest cost is not by any means a simple job.

So we have to consider "cost," and that needs definition. For our present purpose there are two costs; which of the two is meant should always be made clear, and they must be considered separately. They are First Cost and Annual Cost or, since it is better to avoid the use of the same word, Annual Charges. Frequently these two are mutually antagonistic and it is necessary to settle the principles which are to govern selection. For example: Assume a situation in which there is as yet no plant installed and let there be two alternative ways of achieving the results required, A and B as below:—

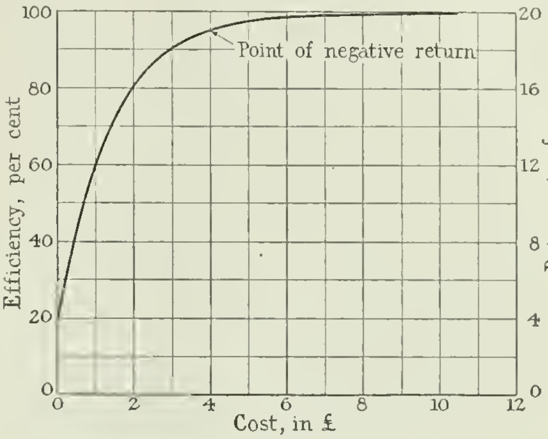


FIG. 2.

| | *Alternative A.* | *Alternative B.* |
|---|---|---|
| | First Cost £10 000. | First Cost £15 000. |
| Annual charges— | £ | £ |
| Return on capital .. | 500 | 750 |
| Depreciation .. .. | 600 | 450 |
| Maintenance .. .. | 500 | 300 |
| Operation .. .. | 900 | 600 |
| | 2 500 | 2 100 |

Annual Charges for A = £2 500
,, ,, B = £2 100

It is evident here that although alternative B requires more capital, yet it is worth while to expend the greater sum because the annual charges are less, so that either a reduced sum can be asked for the product or, since the results achieved are the same, the cash for the product can be the same and an excess profit made.* If, therefore, capital is available and if all risks are properly included in the computations, it is usual and correct to select on the basis of annual charges rather than on the basis of first cost. If capital is not available it may be necessary to select on the basis of first cost, but that is equivalent to *force majeure*, not selection.

---

* See F. GILL and W. W. COOK: "Principles involved in computing the Depreciation of Plant," *Journal I.E.E.*, 1917, vol. 55, p. 138.

If, then, selection is to be made on the basis of annual charges, it is necessary to have these annual charges as accurate as practicable and they may not be lightly treated by rough approximations which may lead to serious error in selection. Now, obviously, the figure of 10 per cent for capital charges which is constantly used in the few engineering discussions on economics is just such a rough approximation which cannot possibly be true for all the cases of varying life and conditions for which it is used. In the example just given, if capital charges (i.e. return on capital plus depreciation) had been taken at 10 per cent, the total annual charges for A and B would have been equal, and the choice would wrongly fall on alternative A because of the lower first cost. The only virtue which the 10 per cent possesses is that it is easy to calculate !

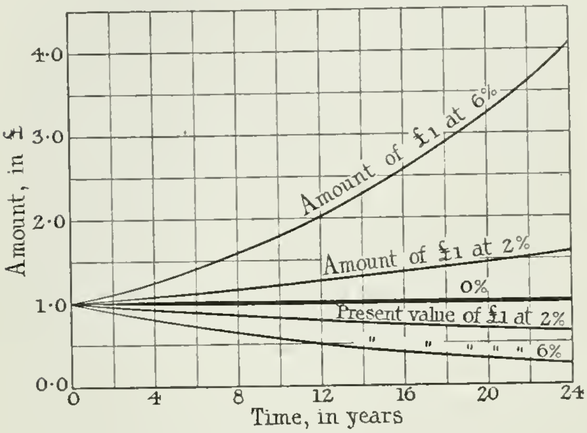


FIG. 3.

Let us look then at the items which go to make up the annual charges and see on what they depend.

*Return on capital outlay*, frequently termed interest ; this must be treated as a charge, because no engineer, in the absence of special circumstances, is justified in constructing plant which will not pay an adequate return on its own first cost. The amount of this return will depend upon the amount of capital expended (which may include charges to capital during construction), and upon the credit of the owner of the plant in the then state of the money market. It may, for example, be $4\frac{1}{2}$, 5, 6 or 8 per cent per annum and therefore it may vary according to the credit of the one for whom the work is to be constructed, and the frequency and amount of further capital expenditure will also affect it.

*Depreciation.*—I define this as (1), "renewals," being provision for the diminution in value of plant in place, by reason of causes *outside* the control of the owner (e.g. age, wear, accidents), and (2), "improvements," being provision to enable him to take the plant out of commission before its physical life is exhausted, that is, by reason of causes *within* the control of the owner, sometimes referred to as "obsolescence."

The money required annually as provision against depreciation will depend upon the life of the plant chosen, which in turn depends on the conditions under which it will work, and the kind of plant selected. The credit of persons will also be involved, since the money put away each year should earn interest ; unless it is so put away in some form or another, the growing financial liability may become overwhelming. The amount will also depend upon the method of treating the provision for depreciation ; but since this part of the subject is too large to be dealt with now, it will be assumed, for the purpose of this discussion, that the sinking fund method will be used. Note that the depreciation provision is to replace the capital expended, not to replace the plant ; this may cost more or less.

*Taxes.*—These will largely depend on political decisions and on whether the owner is subject to taxation.

*Insurance.*—This will largely depend upon the kind of plant used and upon whether or not any owner, in fact, recognizes his liability to provide for insurance as an annual charge.

*Administration.*—This will depend upon the plan of operation and organization followed by each individual owner of plant.

*Maintenance.*—This will depend upon the degree or quality of maintenance desired by the owner, upon the kind of plant constructed and upon its situation.

*Operation.*—This will depend upon the kind of plant employed, but may also be affected by the individual conditions applicable to each job.

In all these cases there is the common element of the employment of money during a period, and so the conditions under which money may be employed must be part of the engineer's knowledge. This leads us to the matter of interest, which may briefly be put somewhat as follows : Money, being merely credit, may not be held for nothing ; the mere possession of money or of materials and plant for which money might be exchanged, involves a continuous charge so long as the possession lasts.

If I put, say, £100 away in a stocking and leave it there safely and draw my £100 from the stocking in 10 years' time, it has cost me something. For if the market rate for money is, say, 4 per cent per annum, that £100 if invested at 4 per cent compound interest for 10 years would have grown to £148, and so the policy of putting the money away uselessly has involved the loss of £48.

If the market rate had been 6 per cent per annum the loss would have been £79 and, of course, if the time had been longer, say 20 years at 6 per cent per annum, the loss would have been still greater, viz. £220. Parenthetically, one may say that it was this failure to use wisely the credit placed at his disposal that brought down the rebuke on the head of the unprofitable servant.

We may illustrate this matter by considering it somewhat in the light of financial perspective. Fig. 3 shows the amount to which £1 will accumulate if it earns interest for a number of years, and also its present value if its payment is deferred for a number of years. It will be obvious that an expenditure of £1 first cost now is more serious than an expenditure of £1 first cost deferred for a number of years. Hence it would not be correct to add to-day's first cost and deferred first cost; they must be brought to some common time basis, generally the present time. As an example, if a scheme involves the expenditure of £100 now and £100 in 10 years' time, the total present value of the expenditure (assuming 6 per cent per annum) is made up as follows:—

| | £ |
|---|---|
| Now .. .. .. .. | 100 |
| Deferred: 100 × 0·56 .. .. | 56 |
| Total present value .. .. | £156 |

In the same way Fig. 4 shows the amount to which a payment of £1 per annum (called an annuity) will accumulate if it earns interest for a number of years, and the present value of the annuity.

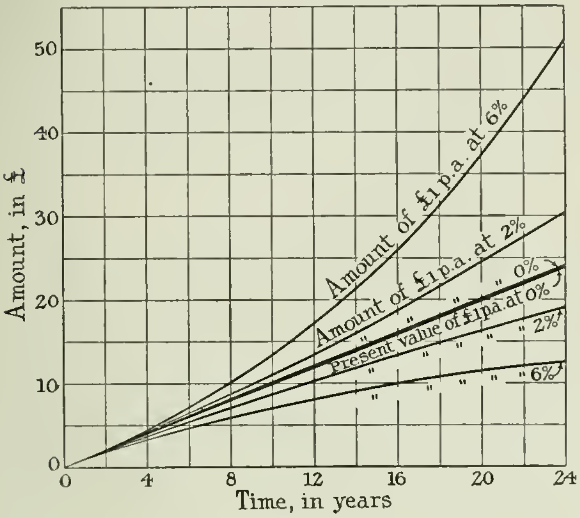


FIG. 4.

If £1 per annum at 6 per cent per annum will increase in 20 years to £36·79 then it is obvious that to accumulate £1 at the end of 20 years at 6 per cent per annum will require an annual payment of 1/36·79 = £0·027, and so sinking-fund tables are formed, being the reciprocal of the amount of £1 per annum at the various rates of interest.

Fig. 5 illustrates sinking-fund payments, both if interest is disregarded and if it is taken at 6 per cent; there is shown also the ratio between the two. Now in engineering computations of depreciation, interest is frequently disregarded, but it must be remembered that accurate annual charges cannot be ascertained unless the rate of interest, appropriate to the occasion, is taken into account.

Perhaps enough has been said to proceed now to illustrate the point by reference to particular cases, but the treatment must be very approximate in order to cover the ground in the time available.

(1) First of all let us take a case of opening a street in which to lay ducts to contain cables. The rate of growth has been estimated, the cost of breaking up and restoring the street surface is known; also the excavation cost and how it varies with the number of ducts; the cost of the ducts laid; the financial rates such as interest, depreciation, etc. Suppose we require to have 6 ducts now and 3 more later on, then our problem is whether we shall lay the additional 3 ducts now or wait until they are required. We may approach this roughly as follows: Assume the cost of a trench containing 9 ducts to be 45s. per yard run, the cost of the same with 6 ducts is 32s., therefore the additional cost of the 3 ducts if laid now is 45 − 32 = 13s. per yard. Assume also that the cost of 3 ducts laid independently is 22s. per yard run. Further assume that the full charges on capital are 8 per cent per annum.

| | s. |
|---|---|
| The extra cost *now* per yard is .. .. | 13 |
| The extra cost *deferred* per yard is .. | 22 |

The ratio of these is 13/22 = 0·59. From the 8 per cent interest tables we see that 0·59 is the present value of £1, 7 years hence, so that if the growth is such as to require the extra ducts within 7 years it is economical to lay them while the ground is open. Just what is the most economical period to plan for (there is such a period and it is important) cannot be treated in such a hasty manner.

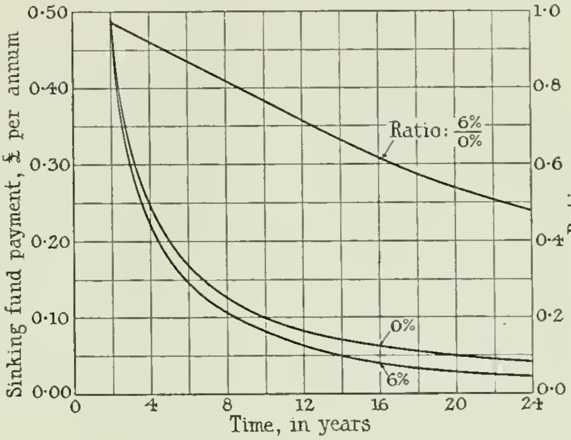


FIG. 5.

(2) You may say this is just common sense, and so it is, but the sense is not common. To demonstrate this, let me quote Professor Miles Walker's book on "The Specification and Design of Dynamos" (1915), where on pages 495 *et seq.* he says:—

"We may wish to build the generator as cheaply as possible, using the smallest amount of wire that will give us a temperature rise not greater than the guaranteed temperature rise.

"We may be ruled by considerations of efficiency and settle the number of watts which are to be wasted in shunt excitation.

"A large number of buyers will buy the cheapest machine that appears to be good enough for their purpose. Other buyers, on the other hand, recognize that very often a more expensive machine of higher efficiency will save more in the year than the interest on the extra cost. With power at one halfpenny per unit, a kilowatt of twelve hours a day for 300 days in the year will cost £7 10s. per annum. Capitalizing this at 10 per cent we get £75. It would in many cases be worth while for a buyer to pay £75 more for a machine which will save him 1 kilowatt in the shunt excitation.

"In the machine worked out on page 489 [75 kW, 525 volts, 25 cycles, 750 r.p.m.] the loss in the shunt coils and rheostat is 820 watts. The weight of copper is 64 kilograms. This is almost the minimum weight we could use if we are to meet the temperature guarantees. It would be good policy to increase this weight and make a saving in shunt losses if the buyer would recognize the fact, and pay a greater price. There is room for another 1 500 turns, which would reduce the losses by 250 watts. This, on the above basis of calculation, could be capitalized at £19, and yet the cost of the extra 1 500 turns would not be more than £8. Yet so keen are many buyers to buy the cheaper [i.e. at first cost] machine, heedless of small differences in efficiency, that the practice of using the least possible quantity of copper pays from the manufacturer's point of view.

"The same want of regard on the part of the buyer for small differences in efficiency leads many manufacturers to use ordinary dynamo steel of good quality at (say) £11 per ton rather than alloyed steel at £25 per ton. In the present case, with ordinary iron the iron losses work out at 840 watts, whereas with alloyed steel they could be reduced certainly to 600 watts. The saving of 240 watts is worth about £18, and the cost of the alloyed iron would not be more than £5. Some buyers are beginning to recognize these facts, and the future may see a very great increase in the efficiency of small generators and motors."

One is tempted to ask where were the buyers educated, that they should have their minds so set upon first cost as not to recognize that the apparently dearer machine is really the cheaper one.

But this matter of 10 per cent capital charges never appeals to me, so it will do no harm to take the case more in detail. Let us assume the following, using the same figure of £8 as the increased first cost :—

| | *Case A* | *Case B* |
|---|---|---|
| First cost .. .. .. | £352 | £352 + £8 = £360 |
| Scrap value, 15 per cent .. | 52 | 54 |
| Depreciable amount .. | £300 | £306 |

The return on capital being taken at 6 per cent per annum, the sinking fund to redeem the depreciable amount will also be at 6 per cent per annum. Let the life be assumed at 15 years.

Our annual charges will be as follows :—

| | | |
|---|---|---|
| Return on capital, 6 per cent on £352 | = £21·1 | on £360 = £21·6 |
| Sinking fund, 6 per cent 300 × 0·043 | = £12·9 | 306 × 0·043 = £13·2 |
| | £34·0 | £34·8 |

But by adopting the machine in Case B we are saving 0·25 kW at £7 10s. per kW for 300 twelve-hour days in a year. Hence the annual charge of the machine in Case A should be increased by 0·25 × £7 10s. = £1·9.

Our annual charges will therefore be :—

Case A.—Annual charge £34·0 + £1·9 = £35·9
Case B.—Annual charge = £34·8

In other words a saving of £1·1 per annum is effected by adopting the machine in Case B, which is £8 dearer in first cost.

Now we find that if the machine in Case B were to cost £372 initially, that is £20 more in first cost than the machine in Case A, the annual charges would be the same in both cases. (Notice that it does not "pay" to buy the machine at £20 additional first cost, that is the additional first cost at which the two machines equate, but it does "pay" to give the additional £8 first cost, and it would "pay" to give any increased additional amount up to £20.)

(3) In the scheme for sanctioning loans by local authority undertakers the Electricity Commissioners "adopt as a general basis the principle of sanctioning separate repayment periods determined by the estimated life of the various assets (land, buildings, plant, etc.)."

Some of the maximum periods are :—

| | Years |
|---|---|
| Land, freehold .. .. .. .. | 60 |
| Buildings .. .. .. .. | 30 |
| Plant and machinery .. .. .. | 20 |
| H.T. trunk transmission mains .. | 40 |
| Overhead lines .. .. .. .. | 25 |
| Mains and services .. .. .. | 25 |
| Meters .. .. .. .. .. | 10 |

Presumably the period for freehold land is based upon something other than the life of the asset.

In cases where the generating plant is likely to be superseded the term is less and is usually 15 years.

I understand that with regard to steam plant the maximum loan period for turbo-generators is 20 years and for Diesel engines 15 years. I am not questioning the correctness of these lives when I point out (again assuming 6 per cent interest, but this time without scrap value, for simplicity) that this difference in the loan period will have an effect on the economics of the matter because the sinking fund for a 15-year period at 6 per cent is 57 per cent greater than for a 20-year period.

(4) Let us take another and very usual kind of case, and work it out in detail.

Let us assume a 30 ft. pole line 1 000 ft. in length, situated in a roadway. The pole line has four 8-wire arms with No. 14 S.W.G. iron wire for distributing purposes. It is expected that in any event this route will have to be removed from the roadway at the expiration of 6 years. The line will not carry any further arms, and additional facilities can only be provided by installing a 25-pair aerial cable on this pole line. There are at present 16 pairs of wires branching off the route for subscribers' circuits (referred to later as branches) and the growth is such that a further 24 circuits will be wanted within 6 years, which then represents the ultimate requirements. When this pole line is abandoned the new distributing system that replaces it will consist of a 25 ft. pole line 1 000 ft. long, built in an alley-way behind the houses and carrying a 50-pair aerial cable with suitable terminals.

The question is whether it would be cheaper to place the 25-pair cable on the existing pole line, utilize it for 6 years and then build the new line (recovering the existing line), or to build the new line and take down the roadway line at once. After 6 years the construction would be the same in both cases, so it is only necessary to consider the costs for a period of 6 years. The figures given as "first costs" and "annual charges" are for the purpose of illustrating the two cases only, and must not be taken as being in any way representative figures. Money is assumed to earn 6 per cent per annum, and we work out the two cases as follows:—

From these calculations we obtain the following figures:—

| | |
|---|---|
| *Case I.*—Present value of charges | £256·79 |
| *Case II.*—Present value of charges | £207·22 |
| Difference in favour of Case II | £49·57 |

Therefore it is cheaper to abandon the existing roadway line at once.

(5) Another illustration, and one of a kind which may affect the young engineer before he comes to the day of big things, is taken from relay design. When relays have to remain in operation for a considerable time the annual power charges become important and the design must be such as to give minimum annual charges. In Fig. 6 is shown a group of curves for a type of relay, and these illustrate how nearly the minimum annual charges have been attained for a

*Case I.—Existing Pole Line retained for Six Years.*

| Item | First cost | Annual charges | | Present value of charges |
|---|---|---|---|---|
| | £ | % | £ | £ |
| (1) Existing Plant. | | | | |
| (*a*) 30 ft. poles, stays and steps | 30 | 12 | 3·6 | |
| (*b*) Arms and wire | 50 | 18 | 9·0 | |
| (*c*) 16 existing branches at £2 each | 32 | 18 | 5·76 | |
| (2) 1 000 ft. 25-pair L.C. cable, including suspension strand and terminals | 80 | 15 | 12·0 | |
| | | | 30·36 | |
| Present value of £30·36 per annum for 6 years = 30·36 × 4·917 (see Fig. 4) | | | | 149·28 |
| (3) 24 branches during 6 years, equivalent to all deferred 3 years and existing for 3 years more, 24 at £2 each | 48 | 18 | 8·64 | |
| Present value = annual charges × present value 3 years × present value 3 years deferred = 8·64 × 2·673 (see Fig. 4) × 0·839 (see Fig. 3) | | | | 19·38 |
| (4) Transfer loss upon recovery of pole route, cable and branches 6 years hence, say £125 at 0·705 (see Fig. 3) | | | | 88·13 |
| Total present value of all charges | | | | £256·79 |

*Case II.—Build New Line and take down Existing Pole Line at once.*

| Item | First cost | Annual charges | | Present value of charges |
|---|---|---|---|---|
| | £ | % | £ | £ |
| (1) Erection of 25 ft. poles and stays | 21 | 12 | 2·52 | |
| (2) Erection of 1 000 ft. 50-pair cable, suspension strand and terminals | 110 | 15 | 16·5 | |
| (3) 16 existing branches at £2 | 32 | 18 | 5·76 | |
| | | | 24·78 | |
| Present value of £24·78 per annum for 6 years = 24·78 × 4·917 (see Fig. 4) | | | | 121·84 |
| (4) 24 branches during 6 years, equivalent to all deferred 3 years and existing for 3 years more, 24 at £2 each | 48 | 18 | 8·64 | |
| Present value = annual charges × present value 3 years × present value 3 years deferred = 8·64 × 2·673 (see Fig. 4) × 0·839 (see Fig. 3) | | | | 19·38 |
| (5) Transfer loss on route taken down now, say £66 | | | | 66·00 |
| Total present value of all charges | | | | £207·22 |

certain standard type, when the relay, without any change whatever, is in operation for periods of from 60 to 600 minutes per day. Because of varying conditions in different places, relative cost figures are shown; the main points are, the principle that even apparently simple apparatus design requires the application of economics, and the fact that this illustration is taken from just the kind of work on which the young engineer is likely to be engaged.

Let us refer to one more illustration of a system in which certain definite results are to be reached but which may be achieved in several different ways. Obviously there will be some relation between the money which may be spent on one part and that which may be spent on another part so as to obtain the lowest total cost; in other words, we obtain a balance or equilibrium between the relative costs and, as previously stated, these costs may be analysed from the points of view of both first cost and annual charges.

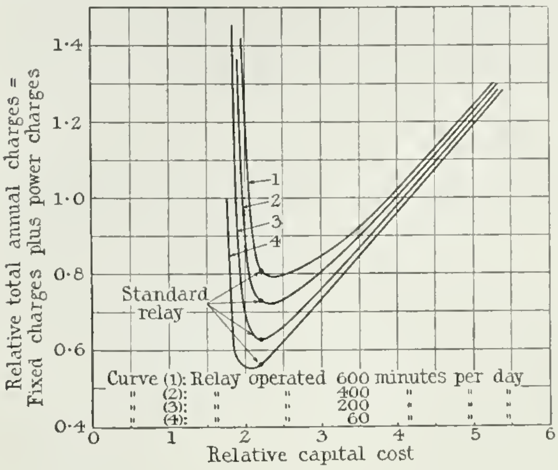


Fig. 6.

In engineering any work and particularly in engineering any system it is impossible to do it economically unless market prices are known. For with the market in one state it may be profitable to spend more money on, say, iron and less on copper, or vice versa, and this cannot be determined without prices. When markets are steady, standard prices can be used for long periods, but when they are unsteady the engineer must obtain prices before he can select.

I do not believe that courses of study are necessary to treat this matter in the schools. It rather requires an attitude of mind on the part of the teacher, in order that this kind of treatment shall be applied sometimes to the problems dealt with. One great objection to the present method is that because students do not get this training at college they have to acquire it either by their own efforts or by the aid of men in practice and not by the aid of skilled teachers.

It is sometimes suggested that these questions of annual charges are, after all, matters of accounting and are not really of interest to engineers. That this view is entirely wrong is at once seen by considering the separate occasions on which these charges are important. Thus:—

"(*a*) Before plant of any magnitude is constructed it is necessary to ascertain which of alternative plants is the economical one to employ for the purpose.

(*b*) Either before construction, or soon after, it may be necessary to determine the rates to be charged.

(*c*) After the plant is in operation, costs have to be ascertained and profits determined.

(*d*) When it is proposed to scrap any plant in favour of a larger or more efficient type, it is necessary to compute the savings which will be effected and the loss of capital involved. Depreciation enters into both calculations.

(*e*) In the event of a sale of plant on what are known as 'tramway terms,' depreciation of the plant has to be ascertained on one basis, and

(*f*) If the business is sold as a going concern it may be necessary to compute the depreciation on another basis." *

My object in bringing this matter before you young engineers is to try to interest you in a very important part of the work that you will ultimately undertake. These principles are necessary even in small matters; they are vital to the safe handling of large engineering schemes involving great expenditure. Some of you may be called upon to be responsible for the wise spending of great sums of money, and to do this you must work along the principles which I have briefly sketched. With an adequate knowledge of engineering economics added to the more usual engineering knowledge, you may go far, increase the reputation of your profession, and do useful work; without it you are not safe guides as to the expenditure of large sums of money.

---

* F. Gill and W. W. Cook: "The Depreciation of Plant," *Journal I.E.E.*, 1917, vol. 55, p. 167, slightly altered.

# INDUCTION MOTORS USED AS SYNCHRONOUS MACHINES.*

By S. V. Ganapati and R. G. Parikh, B.Sc., Students.

(*Paper received 11th November, 1922.*)

## Summary.

The object of the paper is to determine the overload capacity of an induction motor when operated synchronously, and the pulling-in capacity at synchronism. Incidentally, in view of suggestions made in this connection in periodicals, experimental data have been obtained for (1) two methods of using a star-connected rotor for excitation, and (2) the resulting heating of rotor windings under the two methods of excitation. Further readings have been taken so as to enable curves of efficiency, power factor and stator current to be drawn.

The conclusions are that the advantages of synchronous operation of induction motors are most pronounced when the method is utilized at times of light load and up to about 70 per cent of full load. At heavier loads there is a loss of efficiency and only a slight improvement in power factor. Owing to the necessity of adjusting the excitation to the load, synchronous operation is unsuitable in the case of fluctuating loads.

## Introduction.

The most serious defect of the polyphase induction motor—its low average power factor—has exercised the ingenuity of numerous inventors, and many attempts have been made to improve the performance of the motor in this respect. Development has proceeded along two main lines: (1) By providing the motor with auxiliary external devices known as phase advancers; and (2) by modifying the design of the motor so that, while retaining its desirable starting features, it could be run as a synchronous machine, with all the advantages of power factor control, when once started. A great deal of interest has recently centred on this problem, as evidenced by the comparatively large number of papers published on it.†

In this paper a brief account is given of some results obtained with an ordinary three-phase induction motor ($7\frac{1}{2}$ b.h.p., 100 volt, 50 periods, 1 450 r.p.m.) having star-connected windings. The machine was coupled to a direct-current generator which formed a convenient load, and, after having been run up to speed, was excited by means of direct current supplied to the rotor windings through the slip-rings.

## Two Methods of Using Star-connected Rotor Winding as Exciting Winding.

Two methods of using a star-connected rotor winding for d.c. excitation are available, namely, (1) two windings only in series, with the third left out of circuit entirely; and (2) two windings in parallel, both being in series with the third. These two methods are represented in Figs. 1 (*a*) and 1 (*c*).

Let Fig. 1 (*a*) represent the circuit diagram of the rotor, the full-line arrows denoting the directions (assumed positive) for the currents in the windings AO, BO and CO, under normal operation as an induction motor. Fig. 1 (*b*) is the corresponding space-vector diagram, which is drawn as follows. The lines OA, OB and OC give the directions of the magnetic axes of the three rotor windings OA, OB and OC of Fig. 1 (*a*), the angles between these axes being 120 electrical degrees. The magnitude of each flux is represented by the length of the corresponding vector in Fig. 1 (*b*). When the rotor is run short-circuited under normal conditions of operation of the machine as an induction motor, the vectors in Fig. 1 (*b*) representing the fluxes due to the rotor currents are alternating vectors having time-phase differences of 120°, and their resultant is, as is well known, a simple rotating vector of constant length. When only two phases, OA and OB, are used [as shown in Fig. 1 (*a*)] for d.c. excitation, the corresponding vectors in Fig. 1 (*b*) are equal and of constant length. Further, the direction of the vector OB must be reversed, since with the connections shown in Fig. 1 (*a*) the current in OB is negative. Thus the resultant flux, obtained by com-

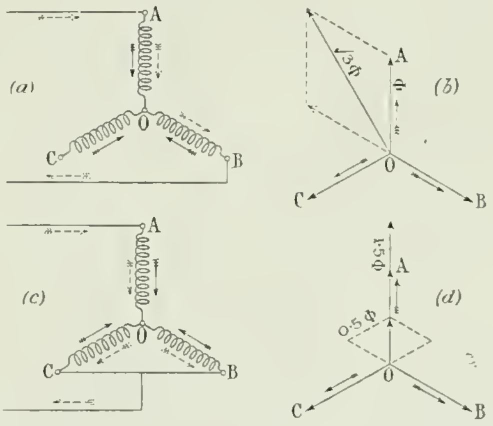


Fig. 1.—Circuit and vector diagrams for series and parallel arrangements of rotor windings.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† The following references may be useful: A. Soulier: *Revue Générale de l'Électricité*, 1919, vol. 5, pp. 505 and 831; R. G. Warner and A. E. Knowlton: *Electrical World*, 1920, vol. 76, p. 1021; J. Le Monnier: *Revue Générale de l'Électricité*, 1920, vol. 8, p. 687; J. Gewecke: *E.T.Z.*, 1921, vol. 42, p. 1217. Mr. L. H. A. Carr's paper (*Journal I.E.E.*, 1922, vol. 60, p. 165) appeared after the experiments described in the present paper had been completed.

pounding OA and OB reversed [as shown in Fig. 1 (*b*)], is $\sqrt{3}$ times the flux due to either phase when acting alone. Considering now the second arrangement,* Fig. 1 (*c*), with the same current in the winding OA as before, the currents in the other two windings are each half that in OA, and negative. The vector diagram for this case, Fig. 1 (*d*), gives the magnitude of the resultant flux equal to 1·5 times that due to the phase OA. Hence we see that, with a given exciting current, the stator voltage obtained in case (1) is $\sqrt{3}/1\cdot5 = 1\cdot15$ times the voltage with the second arrangement; or, in other words, to develop a given stator voltage the first arrangement—that of two phases in series—requires less exciting current.

It was thought desirable to verify these conclusions, and accordingly open-circuit tests were made employing the two methods of excitation. The results are given in Fig. 2. The ratio of the exciting currents for a given stator voltage varies from 1·11 to 1·18, the average value being 1·15. Fig. 2 also shows the short-circuit characteristic and the variation of the synchronous impedance with excitation.

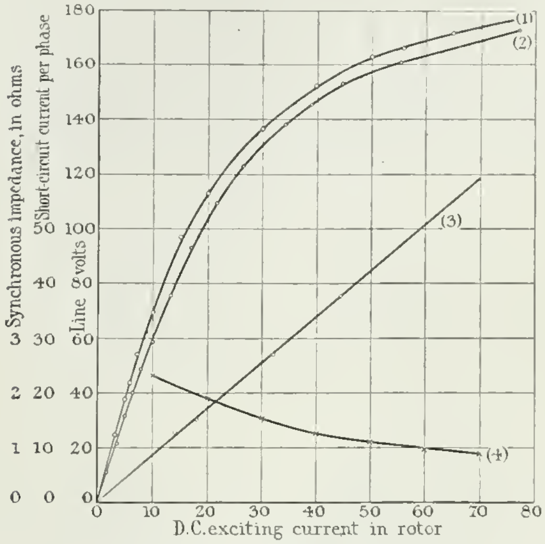


FIG. 2.—Curves of magnetization with series and parallel arrangements of rotor windings; short-circuit characteristic and synchronous impedance curve.

(1) Magnetization curve with d.c. excitation in rotor, using two windings only in series.
(2) Magnetization curve, using two windings in parallel and in series with the third.
(3) Short-circuit test with d.c. excitation in two windings of the rotor in series, and stator short-circuited.
(4) Synchronous impedance.

## HEATING OF ROTOR WINDING.

Considering next the copper losses in the windings in the two cases *for a given stator voltage*, we have for the copper losses in the first case $2rI^2$, where $I$ is the exciting current, and in the second case

$$[r + (r/2)]\,[(\sqrt{3}/1\cdot5)I]^2 = (3/2) \times (3/2\cdot25)rI^2 = 2rI^2$$

Thus the total copper losses are the same in the two cases, but their distribution is different. In order to study the effect of this difference of distribution, tests were made using an excitation of 55 amperes in the first case and 65 amperes in the second case, these being the currents required to generate the same voltage in the stator. The machine was in each case run for seven hours continuously, and the temperature-rises were obtained by the increase-of-resistance method. The curves of temperature-rise are given in Fig. 3. These show that the plain series arrangement is the better of the two, as in the second arrangement the winding carrying the full current reaches a higher temperature than that of the series-connected coils of the first arrangement.

## OVERLOAD CAPACITY.

The following procedure was adopted for the purpose of determining the overload capacity at various excitations. The rotor excitation being maintained constant, the motor load was increased by a series of steps. At each value of the load the motor was allowed to run for some time in order to make sure that it would carry the load continuously without dropping out of step. Readings were taken of input, output, voltages and currents. The load was increased by small amounts at a time, until the motor dropped out of step. This gave the overload capacity for the particular excitation used; each value so obtained was verified by repeating the set of readings. The test was carried out for a number of different excitations up to an excitation of 65 amperes, corresponding to about 55 per cent overload on the rotor windings. The results obtained are shown in curve 2 of Fig. 4; the theoretical curve 1 gives the calculated overload capacity corresponding to various excitations, and was obtained from the circle diagram for the machine considered as a synchronous motor. The overload capacity increases with the excitation very nearly according to the straight-line

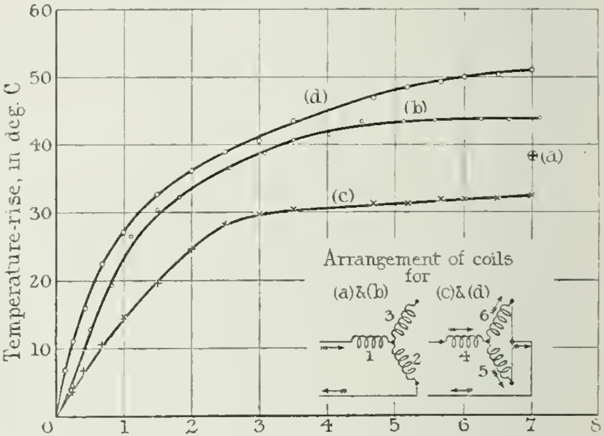


FIG. 3.—Curves of temperature-rise.

Curve (*a*).—Temperature-rise of coil 3.
,, (*b*).— ,, ,, coils 1 and 2.
,, (*c*).— ,, ,, coils 5 and 6.
,, (*d*).— ,, ,, coil 4.

---

* A delta arrangement of rotor windings is exactly identical with this second arrangement, both as regards voltage developed by the stator and heating; this answers the question raised by Mr. A. M. Taylor in the *Electrician*, 1921, vol. 86, p. 386.

law, just as in the case of a synchronous motor of ordinary design. The curve bends downwards at high excitations, owing to the saturation of the core. The true synchronous motor has a large overload capacity because of the large ratio of field ampere-turns to armature ampere-turns, or, in other words, because of the relatively long air-gap. The demagnetizing effect of the armature current is relatively small. In the induction motor, on the other hand, the air-gap is small and the demagnetizing effect consequently great. Hence the induction motor, when used synchronously, is very sensitive at lagging power factor and becomes unstable; but, when running with a leading current, the magnetizing effect of the stator ampere-turns renders its operation stable. In the particular machine experimented on, the maximum load under synchronous operation is 9·0 b.h.p. with an excitation of 55 amperes, which is within the safe temperature limit. When operated synchronously with the maximum safe exciting current the machine has therefore an overload capacity of 20 per cent.

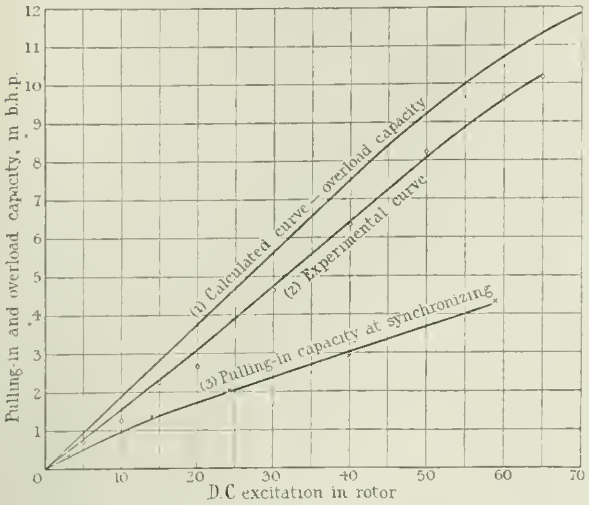


FIG. 4.—Pulling-in and overload capacity of synchronous induction motor.

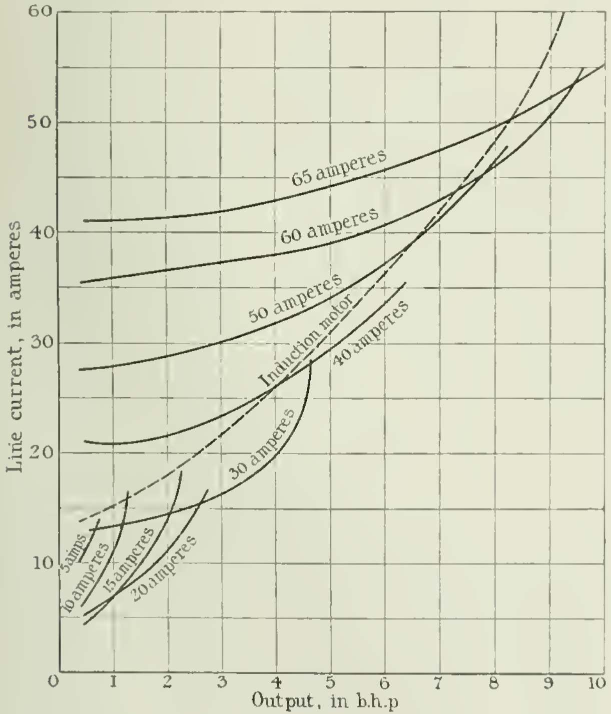


FIG. 5.—Relation between stator current and load at various excitations.

It may be worth while to note here the fact that a synchronous motor of the ordinary type will admit of a large variation in its excitation at all loads. An induction motor, however, is rendered unstable by a relatively small decrease in its excitation. A peculiarity exhibited by the V-curves of the induction motor used synchronously is that the curve joining the points of minimum armature currents bends to the right, whereas in the synchronous motor the gradual shifting of the point of minimum current is first towards lower and then towards higher values of the excitation.

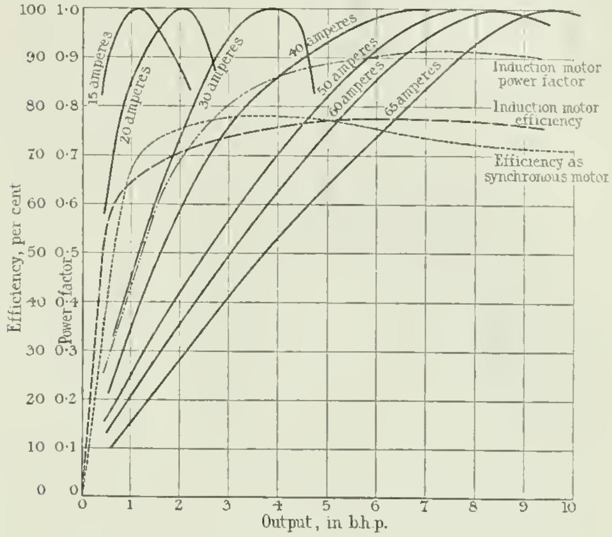


FIG. 6.—Power factor and efficiency curves.

### PULLING-IN CAPACITY.

The next set of tests consisted in determining the pulling-in capacity at the moment of synchronizing, that is, in determining the power corresponding to the torque exerted by the motor at the moment of passing into synchronism. In carrying out these tests the motor was started as an induction motor and the rotor resistances were gradually short-circuited. The motor was then loaded by means of the d.c. generator coupled to it. The d.c. excitation, which had previously been adjusted to a definite value, was applied as soon as the starting resistances were cut out. It was observed whether the motor pulled into synchronism or not. The tests were carried out with different values of the load, and the exact amount of excitation required to synchronize was determined for each load. The results are shown in curve 3 of Fig. 4. It was not possible to determine the pulling-in capacity for loads above 4·3 b.h.p., as the excitation required was beyond the safe temperature limit of the windings.

### STATOR CURRENT AND POWER FACTOR.

In Fig. 5 are plotted curves showing the connection between the stator current and the output of the motor for various degrees of excitation, and for comparison the curve of the stator current corresponding to induction operation is also shown. It will be noticed that when used as a synchronous motor the machine is very sensitive to changes of excitation, the stator current varying between extremely wide limits as the excitation is changed. In this respect the motor differs from the ordinary type of synchronous machine, the excitation of which may be varied considerably without producing correspondingly large changes in the armature current.

In Fig. 6 are plotted the curves of power factor and efficiency. From these it will be seen that the point of maximum power factor shifts rapidly to the right, the ends of the curves being the points at which the motor breaks from synchronism.

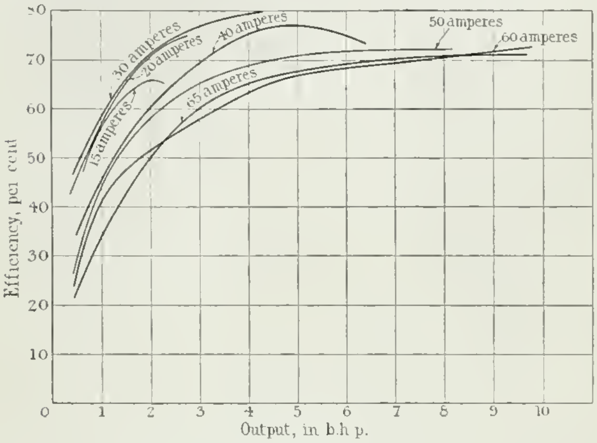


FIG. 7.—Relation between output and efficiency at various excitations.

In Fig. 6 are also given two efficiency curves. One of these refers to the efficiency of the machine as a plain induction motor, while the other gives its efficiency as a synchronous motor when the exciting current is adjusted to give a power factor of unity at each load. From these efficiency curves it will be seen that between about 20 per cent and 70 per cent of full load, the efficiency of the machine used as a synchronous motor is higher than its efficiency as an induction motor, provided that the most suitable excitation is used for each load ; above 70 per cent load the opposite holds good, due to the increased rotor excitation losses.

Fig. 7 gives the efficiency curves corresponding to various constant values of the excitation.

The experimental results from which the various curves were plotted are given in the Appendix.

The authors are greatly indebted to Professor Alfred Hay for suggesting the work to them, for his kindly advice and criticism, and for revising the paper.

## APPENDIX.

### TABLE 1.*

*Synchronous Operation.*

Excitation 5 amperes, 100 volts.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 0·65 | 0·37 | 43·3 | 0·34 | 10·2 |
| 0·76 | 0·47 | 46·2 | 0·38 | 10·8 |
| 0·83 | 0·53 | 48·5 | 0·39 | 11·5 |
| 0·89 | 0·60 | 50·7 | 0·40 | 12·1 |
| 0·99 | 0·71 | 53·5 | 0·39 | 14·0 |

### TABLE 2.

*Synchronous Operation.*

Excitation 10 amperes.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 0·76 | 0·41 | 41 | 0·60 | 6·3 |
| 0·81 | 0·51 | 46 | 0·61 | 6·7 |
| 0·86 | 0·56 | 49 | 0·62 | 7·1 |
| 0·93 | 0·61 | 49 | 0·65 | 7·4 |
| 1·03 | 0·68 | 50 | 0·69 | 7·8 |
| 1·10 | 0·76 | 51 | 0·69 | 8·4 |
| 1·24 | 0·85 | 52 | 0·70 | 9·4 |
| 1·37 | 0·97 | 53 | 0·70 | 10·5 |
| 1·49 | 1·00 | 52 | 0·71 | 11·3 |
| 1·77 | 1·25 | 53 | 0·59 | 16·4 |

### TABLE 3.

*Synchronous Operation.*

Excitation 15 amperes.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 0·76 | 0·43 | 42·0 | 0·82 | 4·3 |
| 0·86 | 0·55 | 47·5 | 0·90 | 4·5 |
| 1·02 | 0·67 | 49·3 | 0·91 | 6·5 |
| 1·29 | 0·81 | 47·5 | 0·97 | 6·8 |
| 1·78 | 1·47 | 62·0 | 0·94 | 10·0 |
| 1·88 | 1·72 | 68·6 | 0·91 | 11·0 |
| 2·23 | 1·97 | 66·5 | 0·89 | 13·5 |
| 2·51 | 2·19 | 65·4 | 0·83 | 16·5 |
| 2·59 | 2·25 | 65·3 | 0·76 | 18·5 |

---

* The final reading in each table is the pull-out point.

### Table 4.

*Synchronous Operation.*

Excitation 20 amperes.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 0·71 | 0·44 | 46·6 | 0·58 | 5·0 |
| 1·14 | 0·85 | 56·1 | 0·80 | 6·8 |
| 1·50 | 1·20 | 60·0 | 0·89 | 8·5 |
| 2·08 | 1·95 | 70·2 | 1·00 | 10·9 |
| 2·38 | 2·31 | 72·6 | 0·98 | 13·0 |
| 2·69 | 2·69 | 75·0 | 0·87 | 16·5 |

### Table 5.

*Synchronous Operation.*

Excitation 30 amperes.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 1·01 | 0·64 | 47·5 | 0·32 | 13·0 |
| 1·29 | 0·96 | 55·8 | 0·44 | 13·2 |
| 1·93 | 1·78 | 69·5 | 0·67 | 14·0 |
| 2·51 | 2·41 | 72·1 | 0·84 | 15·2 |
| 3·25 | 3·35 | 77·2 | 0·98 | 17·4 |
| 4·06 | 4·33 | 80·0 | 0·99 | 22·0 |
| 4·47 | 4·64 | 78·0 | 0·83 | 29·0 |

### Table 6.

*Synchronous Operation.*

Excitation 40 amperes.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 1·16 | 0·54 | 34·4 | 0·21 | 21·0 |
| 2·91 | 2·36 | 61·0 | 0·66 | 21·9 |
| 3·65 | 3·13 | 64·4 | 0·78 | 24·0 |
| 4·31 | 3·80 | 66·1 | 0·87 | 25·9 |
| 4·51 | 4·65 | 77·3 | 0·91 | 26·3 |
| 5·23 | 5·36 | 76·8 | 0·96 | 29·0 |
| 6·50 | 6·35 | 73·3 | 0·99 | 35·5 |

### Table 7.

*Synchronous Operation.*

Excitation 50 amperes.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 1·21 | 0·43 | 26·4 | 0·15 | 27·3 |
| 1·87 | 1·19 | 47·5 | 0·28 | 28·5 |
| 2·48 | 1·76 | 53·2 | 0·40 | 28·6 |
| 2·95 | 2·45 | 62·4 | 0·48 | 29·4 |
| 3·62 | 3·20 | 66·3 | 0·60 | 30·4 |
| 4·18 | 3·75 | 67·2 | 0·68 | 31·2 |
| 5·13 | 4·85 | 71·0 | 0·80 | 33·4 |
| 6·20 | 5·80 | 70·1 | 0·89 | 37·0 |
| 7·70 | 7·27 | 70·8 | 0·99 | 42·0 |
| 8·50 | 8·18 | 72·0 | 0·95 | 48·5 |

### Table 8.

*Synchronous Operation.*

Excitation 60 amperes.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 1·36 | 0·43 | 23·5 | 0·13 | 35·0 |
| 1·87 | 1·05 | 42·2 | 0·20 | 36·0 |
| 2·48 | 1·60 | 48·4 | 0·29 | 37·0 |
| 3·02 | 2·05 | 51·0 | 0·38 | 37·0 |
| 4·23 | 3·41 | 60·5 | 0·56 | 37·5 |
| 5·07 | 4·41 | 65·3 | 0·68 | 38·3 |
| 6·70 | 6·09 | 68·2 | 0·86 | 40·8 |
| 9·10 | 8·80 | 71·0 | 0·99 | 49·5 |
| 9·80 | 9·56 | 73·1 | 0·97 | 55·0 |

### Table 9.

*Synchronous Operation.*

Excitation 65 amperes.

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 1·46 | 0·43 | 21·9 | 0·11 | 41·0 |
| 3·81 | 3·07 | 60·5 | 0·43 | 42·0 |
| 5·33 | 4·75 | 67·0 | 0·61 | 44·0 |
| 6·65 | 6·19 | 69·3 | 0·75 | 46·0 |
| 7·77 | 7·28 | 70·3 | 0·86 | 48·0 |
| 8·55 | 8·00 | 70·4 | 0·93 | 49·0 |
| 10·30 | 10·15 | 74·0 | 1·00 | 56·0 |

### Table 10.

*Asynchronous Operation.*

| Input | Output | Efficiency | Power factor | Stator current |
|---|---|---|---|---|
| kW | b.h.p. | per cent | | amps. |
| 0·60 | 0·40 | 49·7 | 0·25 | 14·0 |
| 0·96 | 0·80 | 62·8 | 0·38 | 14·5 |
| 1·31 | 1·15 | 65·7 | 0·50 | 15·3 |
| 1·96 | 1·79 | 68·2 | 0·65 | 17·5 |
| 2·52 | 2·43 | 72·2 | 0·73 | 20·0 |
| 3·22 | 3·24 | 75·4 | 0·82 | 22·7 |
| 3·77 | 3·80 | 76·0 | 0·85 | 25·7 |
| 4·63 | 4·72 | 76·5 | 0·88 | 30·0 |
| 5·54 | 5·87 | 77·7 | 0·90 | 35·5 |
| 6·44 | 6·68 | 77·9 | 0·92 | 40·3 |
| 7·00 | 7·24 | 77·6 | 0·92 | 44·0 |
| 7·30 | 8·08 | 83·0 | 0·92 | 46·0 |
| 8·20 | 8·57 | 78·5 | 0·91 | 52·0 |
| 9·40 | 9·27 | 74·0 | 0·91 | 60·0 |

# PROCEEDINGS OF THE INSTITUTION.

## 695th ORDINARY MEETING, 22 FEBRUARY, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 15th February, 1923, were taken as read and were confirmed and signed.

The first part of the meeting was taken up by a lecture by Dr. H. W. Nichols entitled "Transoceanic Wireless Telephony" (see page 812), which was followed by a discussion (see page 820).

**Mr. B. Welbourn** then exhibited two cinematograph films illustrating "The Electrification of the Chicago, Milwaukee and St. Paul Railroad Company," in connection with which he made the following remarks:—

"The Chicago, Milwaukee and St. Paul Railroad is the first trans-continental line in the United States of America to make a commencement with main-line electrification. They have done a great pioneer work in electrifying their line at 3 000 volts (d.c.), having behind them, so far as I know, only the experience gained on the Butte, Anaconda and Pacific line, which operates at 2 400 volts and is now worked in close co-operation with the Milwaukee system. The films show that the power is derived from hydro-electric stations, although the stations themselves are not shown, and is transmitted along a single-circuit 100 000-volt three-phase line, which runs parallel with the track for the whole distance. The length of route electrified is approximately 650 miles; it is mainly single line, with turnouts and sidings, the total single-track equivalent being about 850 miles. The electrified portion runs from Tacoma on the west coast right up into the mountains for about 200 miles, and then there is a break in the neighbourhood of Spokane. East of this, the electric system again begins and is continued for over 400 miles. The supply for this system comes chiefly from the Montana Power Company and I think it will be of great interest to supply engineers in this country to know that the railway company has not felt it necessary to provide its own power station, but has been content to rely on the public supply. The 100 000-volt lines are tapped into substations placed, on the average, about 32 miles apart, and the substations, in the aggregate, contain nearly 90 000 kVA of transformer plant. The equipment of each substation consists of two or more 3 000-volt (d.c.) sets, consisting of a synchronous motor to which are coupled two 1 500-volt (d.c.) generators. The catenary equipment is very simple, consisting of a steel messenger wire from which are supported two contact or trolly wires, side by side. It will also be seen from the films that the construction is of the simplest possible character, presumably owing to financial considerations. The poles are of uncreosoted wood throughout and have, I believe, been cut from the forests through which the system runs. On them a number of wires will be seen. At the top is the negative feeder. There are also 4 400-volt (a.c.) signal wires, telephone circuits, load-control wires, and the 3 000-volt (d.c.) feeders. The automatic signalling arrangements are fed by the 4 400-volt (a.c.) wires to which I have referred. At the signalling points this pressure is transformed down first to 110 volts at the pole, and then to 23 volts at the lamp terminals. The track itself is exceedingly interesting to all permanent-way and civil engineers. The films show that at one point the train has to climb a 2·2 per cent gradient. This is the steepest part of the line, but there is, in addition, a 21 mile stretch at a gradient of 1·7 per cent. The maximum height to which the railway climbs at any point is 6 000 feet. The track itself is good, and is ballasted throughout very much in the same way as the lines in this country, so that the dust is kept down to a minimum. A great deal of the interest of the line is centred in the locomotives, of which there are two types, both arranged for regenerative control. There is a gearless type weighing 260 tons and having a continuous rating of 3 200 h.p., and a quill type weighing 284 tons and having a rating of 3 400 h.p. These locomotives, both of which are shown in the films, are fitted with pantagraph collectors, and the current collection is excellent. The action of the pantagraph when passing over the wires at a junction is particularly interesting, and I shall arrange for the film to be slowed down at that point to enable the action to be more readily followed. These films are, I think, of interest to every kind of engineer, but of particular interest to young engineers who are intending to go abroad to earn their living, as they will help them to visualize the sort of conditions they will meet with in other countries."

On the motion of the President, a vote of thanks to Dr. Nichols and Mr. Welbourn was carried with acclamation, and the meeting terminated at 8 p.m.

---

## 696th ORDINARY MEETING, 1 MARCH, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 22nd February, 1923, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A paper by Mr. S. W. Melsom, Associate Member, and Mr. E. Fawssett, Member, entitled "Permissible

Current Loading of British Standard Impregnated Paper-Insulated Electric Cables" (see page 517), being the Second Report of the British Electrical and Allied Industries Research Association on the Research on the Heating of Buried Cables, was read and discussed, and the meeting terminated at 7.50 p.m.

## 28TH WIRELESS SECTIONAL MEETING, 7 MARCH, 1923.

(Held in the Institution Lecture Theatre.)

**Professor G. W. O. Howe, D.Sc.,** Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 7th February, 1923, were taken as read and were confirmed and signed.

A paper by Mr. H. Morris-Airey, C.B.E., Member, entitled "Development of High-power Valves," was read and discussed, and the meeting terminated at 7.45 p.m.

## 697TH ORDINARY MEETING (JOINT MEETING WITH THE ROYAL INSTITUTE OF BRITISH ARCHITECTS), 15 MARCH, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 1st March, 1923, were taken as read and were confirmed and signed.

Messrs. H. M. Sayers and G. W. Page were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows :—

### ELECTIONS.

*Members.*

Dickson, Joseph.
Pickles, Verney.

*Associate Members.*

Allbright, William James.
Conway, John, B.Sc.
Gregory, Harry John, B.Sc. (Eng.).
Harris, Percival Frank.
Henderson, Augustine Stuart.
Khambati, Natvarlal Ranehhodlal.
Little, William Robert.
Stuart, George Cassie I.
Sutthery, Colin Pellatt.
Whittaker, Harry, B.Sc. (Eng.).

*Graduates.*

Burdett, Edward Priestley.
Comerton, James Edward.
Davidson, Harold Stuart.
Eades, John Henry.
Fitzpatrick, Edward Joseph.
Gibbons, William John.
James, Hubert Renshaw.
Knight, Harry Stanley Y.
Macarthur, Neil Brown, B.Sc.
Miller, David McRoberts.
Platt, George Augustus.
Read, Alfred Howard.
Skinner, Edward.
Stead, Charles Cecil.
Ward, Walter.
Whaley, Ralph Stanley.
White, William George.
Wind, Hubert.

*Students.*

Arnott, James Monkman.
Baguley, Eric.
Baldwin, Roy.
Bayliss, Gordon Houston.
Bearman, Cyril Wallace G.
Bourn, Ralph.
Bourn, Wallis.

*Students*—continued.

Bower, Charles William.
Brandon, George Douglas.
Bregazzi, Percy.
Briggs, Reginald McCray.
Brunker, Edward George.
Cater, Charles Osborne.
Child, Thomas William.
Church, Geoffrey Theodore.
Clark, Percy Denby.
Collecott, Francis Robert.
Curphey, George Alfred.
Daniel, Robert Richard.
David, Ronald Paul.
de Alwis, Dionysius Reginald C.
Dean, Harry Pitt, B.Sc. (Eng.).
Dickerson, Leslie Hugh.
Dickinson, David Walter L.
Edwards, Alec Felix.
Emery, Edward.
Emery, Wilfred Daniel.
Epps, Herbert Fletcher.
Frost, J. Leslie.
Gainsford, Guy Bernard.
Garland, Thomas Aloysius.
Gillespie, Colin Arthur.
Griffin, Raymond Walter.
Hague, Charles Kenneth F.
Hale, Thomas Charles.
Hands, Howard Frederic, B.Sc. (Eng.).
Harding, Thomas Victor.
Hegazy, Hamed Mahmoud.
Holroyd, Brian Newton.
Howson, Frank.
Jones, Ivor Idris.
Lake, Vernon Sheridan.
Lee, Williamson.
Lieberg, Owen Stanley.
Lister, Clement Marshall.
McAinsh, Neville James.
McCormick, Joseph Deering.
Macfarlane, John Anthony R.
Mackay, Alexander.
Malcomson, John Ransome.
Mathews, Henry Mends.
Matthews, Richard Cyril.
Middleton, Basil Norman.
Middleton, Hilton.
Morgan, William Reginald.
Morris, Quinton.
Palmer, Archie Emerson.
Paton, Allan Park.
Paul, Cedric Stewart T.
Pegg, Reginald Noel.
Pickerill, Albert.
Pollard, Archibald Hayward.
Pollard, John Amyas G.
Purdon, Edmund Rodney.
Rayner, Frederick John.
Reading, John.
Roche, Alleman Holly.
Rose, William Charles.
Sanyal, Dwijendra Nath.
Scott, William.
Shelley, Arthur Herbert.
Singh, Sidhu Balbir.
Subramanian, Krishna Ayyar.
Subramanian, Mrityunjaya.
Sutcliffe, John Roy.
Thomas, Alfred Joseph.
Thompson, Arthur Frank.
Tweedie, Patrick Graeme.

#### *Students*—continued.

Tyacke, Nicholas Arthur.
Walker, Gerald Nicholson.
Walker, William Kennedy M.
Watt, Andrew.
Westlake, Albert Edward.
White, Edwin James.
Whittle, George Edwin.

#### *Associates.*

Jameson, Charles Godfrey.
Ward, Basil Kendall.

### TRANSFERS.

#### *Associate Member to Member.*

Davies, Albert William.
Gregory, Richard Walter.
Hann, Colin Stuart.
Jack, Hugh, B.Sc.
Jacques, Gerald, Major.
Owen, Alexander Cay.
Robinson, Percival James.
Shephard, Thomas Fredrick G.
Thomson, James Alexander V.
Ward, Francis Morley.

#### *Associate to Member.*

Cable, Matthew.

#### *Graduate to Associate Member.*

Garner, Richard Hough.
Leishman, George Alexander B., Major, M.C.

#### *Student to Associate Member.*

Croft, Edward Hugh.
Firnberg, Leopold Bernard.
FitzGerald, Alan Stewart.
Giller, William Leslie.
Grainger, Ernest James, B.Sc.(Eng.).
Hoseason, Donald Bright.
Lawrence, Frederick Charles, M.C., B.Sc.
Pocock, Geoffrey Crawford.

#### *Associate to Associate Member.*

Bullock, Harold John.

#### *Student to Graduate.*

Boyland, Harold John.
Coles, Carl Featherstone.
Dickson, Robert Thompson.
Johnson, Rowland Alfred.
Newburn, Edgar Allan.
Robson, Charles William.
Sharp, Harry Steven N.
Turrell, Francis Henry.
Walmsley, Thomas.

A discussion took place on "Co-operation between the Architect and the Electrical Engineer" (see page 736), with introductory papers by Mr. Francis Hooper, F.R.I.B.A. (see page 726), and Mr. J. W. Beauchamp, Member (see page 728), and the discussion was adjourned to the Ordinary Meeting to be held on the 22nd March, 1923.

The meeting terminated at 7.38 p.m.

## 698TH ORDINARY MEETING (JOINT MEETING WITH THE ROYAL INSTITUTE OF BRITISH ARCHITECTS), 22 MARCH, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 15th March, 1923, were taken as read and were confirmed and signed.

The discussion on the papers by Mr. Francis Hooper, F.R.I.B.A., and Mr. J. W. Beauchamp, Member, entitled "Co-operation between the Architect and the Electrical Engineer" (see pages 726 and 728), was continued, and the meeting terminated at 7.53 p.m.

## 29TH MEETING OF THE WIRELESS SECTION, 11 APRIL, 1923.

(Held in the Institution Lecture Theatre.)

**Professor G. W. O. Howe, D.Sc.,** Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 7th March, 1923, were taken as read and were confirmed and signed.

A paper by Dr. N. W. McLachlan, Member, entitled "The Application of a Revolving Magnetic Drum to Electric Relays, Siphon Recorders and Radio Transmitting Keys," was read and discussed, and the meeting terminated at 7.50 p.m.

# DIRECTIONAL WIRELESS TELEGRAPHY IN AIRCRAFT.*

By C. K. Chandler, M.B.E., Associate Member.

(*Paper first received 23rd October*, 1922, *and in final form 29th January*, 1923.)

## SUMMARY.

The paper deals with the operation of directional wireless telegraphy in aircraft where the directional aerials are installed in the aircraft.

The main difficulty in this work is to deal with the errors which arise. Curves are given showing the errors obtained, and formulæ are developed showing the factors on which the errors depend. Methods of predicting and correcting the errors are given.

Curves of variation in bearings of transmitting stations are given and discussed. A possible cause of these variations is given.

## THE NEED OF DIRECTIONAL WIRELESS NAVIGATION FOR AIRCRAFT.

The question of air navigation differs from navigation on the sea in that it deals with (1) higher speeds, (2) unknown air currents, which affect the aircraft more than the sea craft, (3) difficulty in obtaining accurate fixes when using the sextant, due to the variable movement of the machine, and (4) large compass errors which may develop due to vibration and swinging of the aircraft, these being much greater than in the case of surface craft.

Further, at night or in fog the navigator of an aircraft is at a loss since he has only an approximate idea of the air currents through which he passes. Due to the high speed and consequent distance travelled these may vary considerably during a journey. Unable to take sights or observe his drift the pilot may get hopelessly lost.

For these reasons air navigation, using directional wireless bearings to give position lines, has been developed, since this is independent of the weather and the time of day.

## METHODS IN USE.

Three methods of using directional wireless are available, and are given below.

(1) The machine transmits a message which is picked up by two ground wireless stations, equipped with directional wireless apparatus. These stations each take bearings and plot them on a chart, the intersection of the position lines giving the position of the aircraft. The position is then signalled to the aircraft. This method suffers from the disadvantage that in time of war it discloses the position of the aircraft to enemy stations.

(2) Directional wireless apparatus in aircraft, with which bearings are taken on any known transmitting station. These bearings are plotted by the navigator in the aircraft, thereby fixing his position.

(3) Directional transmission where a directional wireless station is arranged to transmit a " beam " in one direction only. This beam is arranged to sweep round, so that the wireless operator in the aircraft can hear a signal only when the beam is in his direction. A signal is also sent out when the beam is pointing in, say, a northerly direction ; thus the operator can take the interval of time between the first signal and the instant when the beam reaches him, and, knowing the speed of rotation of the beam, he can get his bearing from the transmitting station. This method suffers from the disadvantage that a large number of stations would be necessary to cover a given area, since the transmitting efficiency is not great.

It is proposed here to describe the directional wireless receiving apparatus in aircraft, giving an account of the factors which affect the working of the apparatus.

## DIRECTIONAL WIRELESS APPARATUS IN AIRCRAFT.

The directional wireless aerial as used in the Royal Air Force consists of two coils at right angles to one another. The coils may be mounted in the wings of the aircraft or on a framework inside the fuselage. This framework can be rotated with respect to the fore-and-aft line of the machine.

When wing coils are used the whole machine must be swung in the air to obtain a bearing. As this method seriously affects the compass and takes a machine off its course, wing coils are only used for " homing," i.e. flying along a radius towards a transmitting station, thus enabling an aircraft to return to its base.

*Method of operation.*—The two coils are connected up as shown in Fig. 1, and the operation is as follows :—A signal is picked up using both coils connected, i.e. with the change-over switch on the right-hand contacts. The change-over switch is moved to the left to include the balance coil, which has the same inductance as the auxiliary coil. This ensures the main coil circuit remaining in tune with the incoming signal. The directional wireless aerial is rotated until the loudest sound is heard in the telephones, indicating that the main coil is pointing approximately towards the transmitting station. The change-over switch is now moved to the right-hand contacts, thus including the auxiliary coil and the reversing switch. By using the reversing switch the energy picked up by the auxiliary coil is caused to be first added to that in the main coil, and then to oppose it, thus giving a difference in signal strength so long as the auxiliary coil is picking up energy. The aerial is now turned until no difference in signal strength is heard as the reversing switch is thrown from side to side. The auxiliary coil is then at right angles to the path of the wave, and the main coil is pointing to the transmitting station, thus giving the bearing of the station from the aircraft.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

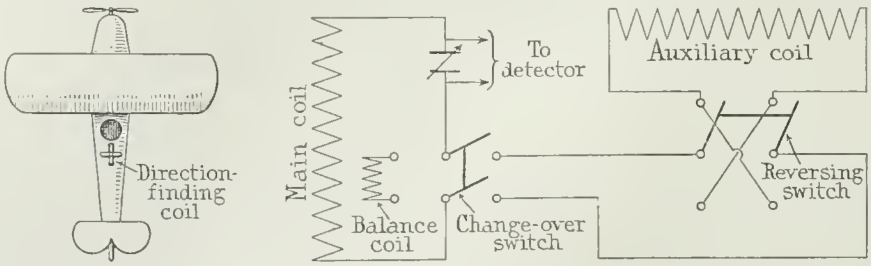


Fig. 1.

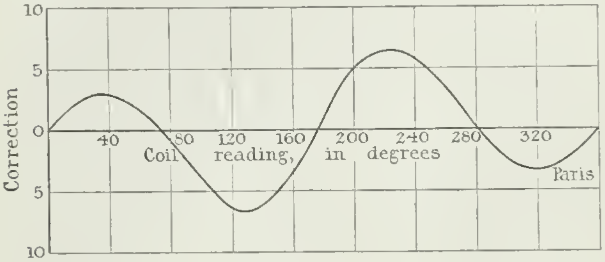


Fig. 2.

### Errors in Bearing.

When the directional wireless apparatus is used in aircraft, it is found that the bearings thus obtained are not correct. Further, if bearings are taken on a known transmitting station for different angles of incidence of the waves on to the aircraft, and the corrections necessary to give true bearings are plotted for different angles of incidence, we get a curve of the form shown in Fig. 2, having maximum values in the four quadrants, i.e. a quadrantal curve in which the error tends to turn the aerial towards the axis of the machine.

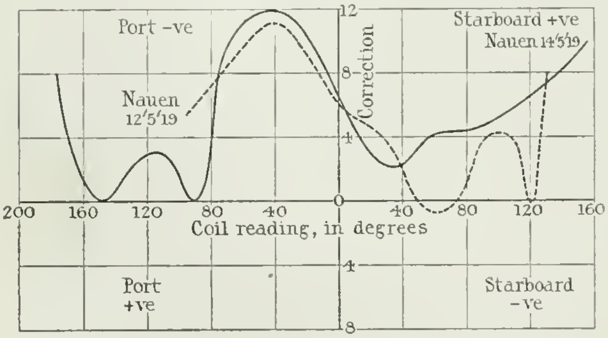


Fig. 3.

In the early days of directional wireless in aircraft it was found to be practically impossible to obtain correct bearings even when error curves had been plotted and the readings corrected. To investigate this a machine was swung on different days before and after flying, and the curves in Fig. 3 were obtained, showing that the errors vary from day to day. Further curves were obtained using different wave-lengths, with the result shown in Fig. 4.

An investigation was then undertaken to find the cause of these variations in error, and if possible to eliminate them. As a result it was discovered that the wireless waves passing the metal work of the machine set up high-frequency currents in the wires. Thus high-frequency magnetic fields are produced which in turn generate voltages in the auxiliary coil. Then, when the auxiliary coil is really at right angles to the incoming wave, it still has a voltage produced in it and therefore we get a difference in signal strength on adding it to or subtracting it from the main coil.

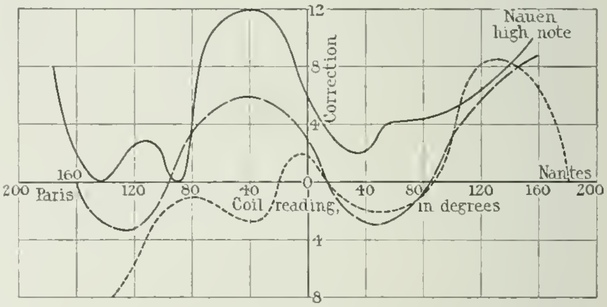


Fig. 4.

In order to get no change in signal strength the aerial system has to be turned round until the energy picked up by the auxiliary coil from the wireless wave is equal in amount and opposite in action to the energy due to the mutual inductance between the auxiliary coil and the metal work. The metal work of the machine can in the first instance be regarded as a coil of wire placed across the aircraft, since the wires are joined together and make metallic contact, and the wings containing most of the long wires are across the machine. The voltage generated in the metal work will then depend on the angle of incidence of the wave, being a maximum when the wave is incident at 90° to the fore-and-aft line of the machine.

Let the maximum R.M.S. value of the voltage generated in the metal work be denoted by $E_m$, then the voltage generated when the wave is incident at an angle $\theta$ from the fore-and-aft line of the machine is given by

$$E = E_m \sin\theta \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The current flowing in the metal work is then given by

$$I = \frac{E_m}{Z} \sin\theta \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $Z$ is the impedance of the metal-work circuit.

The voltage generated in the auxiliary coil by this current is obtained from the expression :—

$$E_a = \omega MI = \frac{\omega M E_m}{Z} \sin\theta \quad . \quad . \quad . \quad (3)$$

where $\omega$ is $2\pi$ times the frequency of the incoming wave ; and

$M$ is the coefficient of mutual inductance between the auxiliary coil and the metal-work circuit.

When the direction-finding aerial is turned until no difference in sound is heard on using the reversing switch, the angle made by the main coil with the axis of the machine is $(\theta \pm a)$, where $a$ is the additional small angle through which the auxiliary coil has been turned in order to neutralize the mutually induced voltage, i.e. $a$ is the quadrantal error for that particular angle of incidence.

The mutual inductance is a maximum when the main coil is pointing along the axis of the machine, so that when the aerial system is turned through an angle $(\theta \pm a)$ the mutual inductance is given by

$$M = M_{max.} \cos(\theta \pm a) \quad . \quad . \quad . \quad (4)$$

Now if $V_a$ is the maximum voltage generated in the auxiliary coil when pointing towards the transmitting station, then the extra voltage required to overcome the mutually induced voltage is given by $V_a \sin a$, so that we can make the following equations :—

$$\sin a = \frac{\omega M_{max.} K}{2Z} \cos(\theta \pm a) \sin\theta \quad . \quad (5)$$

$$K = E_m / V_a \therefore \tan a = \frac{\omega M_{max.} K}{2(Z - \frac{1}{2}\omega MK \sin^2\theta)} \sin 2\theta \quad (6)$$

We must now investigate $Z$ in order to find what values of inductance, resistance and capacity are admissible. In the first place, when the wave is incident at right angles to the axis of the machine the greatest difference of potential will exist between the two extreme ends of the wing wires. In fact these bracing wires form a number of loops in series, in which E.M.F.'s are generated by the incoming signal waves. The ends of the vertical wires are connected together by the bracing wires inside the wings, so that we have a circuit in which flows an ordinary conductive current in parallel with a capacity current which charges the metal work of the machine.

Now consider the errors observed. It will be seen that when the wave is incident at an angle of 45° the error tends to turn the aerial towards the axis of the machine. The auxiliary coil of the aerial is now no longer at right angles to the path of the wireless wave, so that a voltage is generated in it which has the same sense as that generated in the metal work of the machine when this is regarded as a coil lying athwartships. Thus the two voltages are in phase and may be represented as in Fig. 5, where OE is the voltage generated in the metal work and OV the voltage generated in the auxiliary coil.

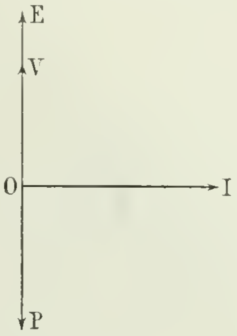


FIG. 5.

Now the voltage induced from the metal-work current must be opposite in phase to OV and can be represented by OP. The current to generate this voltage must be in the phase position given by OI, i.e. it is a lagging current. Thus the capacity current must be small.

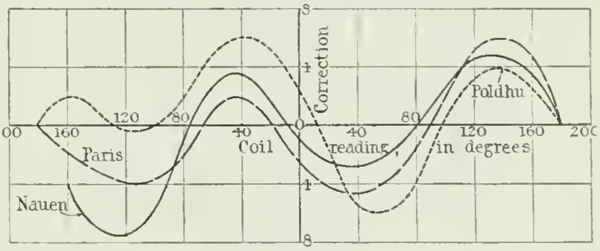


FIG. 6.

The impedance then is made up of two components, inductive reactance and resistance, so that (6) becomes :—

$$\tan a = \frac{\omega M_{max.} K \sin 2\theta}{2\left\{\sqrt{[R^2 + \omega^2 L^2]} - \frac{1}{2}\omega M_{max.} K \sin^2\theta\right\}} \quad (7)$$

The factor $\omega MK \sin 2\theta/2$ is small compared with $\sqrt{[R^2 + \omega^2 L^2]}$, since $M_{max.}K$ is very small. Thus (7) becomes :—

$$\tan a = \frac{\omega M_{max.} K}{2\sqrt{[R^2 + \omega^2 L^2]}} \sin 2\theta \quad . \quad . \quad (8)$$

From this expression it will be seen that if $R$ is small compared with $\omega L$ the true quadrantal error is independent of wave-length but depends on the constants involved in the construction of the machine, such as the size and material of the wing structures and the size of the auxiliary coil of the directional wireless aerial.

In this case, $$\tan \alpha = \frac{M_{max.}K}{2L} \sin 2\theta \qquad . \quad . \quad . \quad (9)$$

In expression (8) $MK$ is a constant for a given machine since it depends only on constructional details, $\omega$ is also a constant for a given wave-length, and $Z$ is the only factor which can vary. The impedance $Z$ is made up of two components, self-inductance and resistance; of these, the inductance should not change, since the metal work is rigidly fixed on the machine; thus it would appear to be the resistance component which causes the variation in quadrantal error.

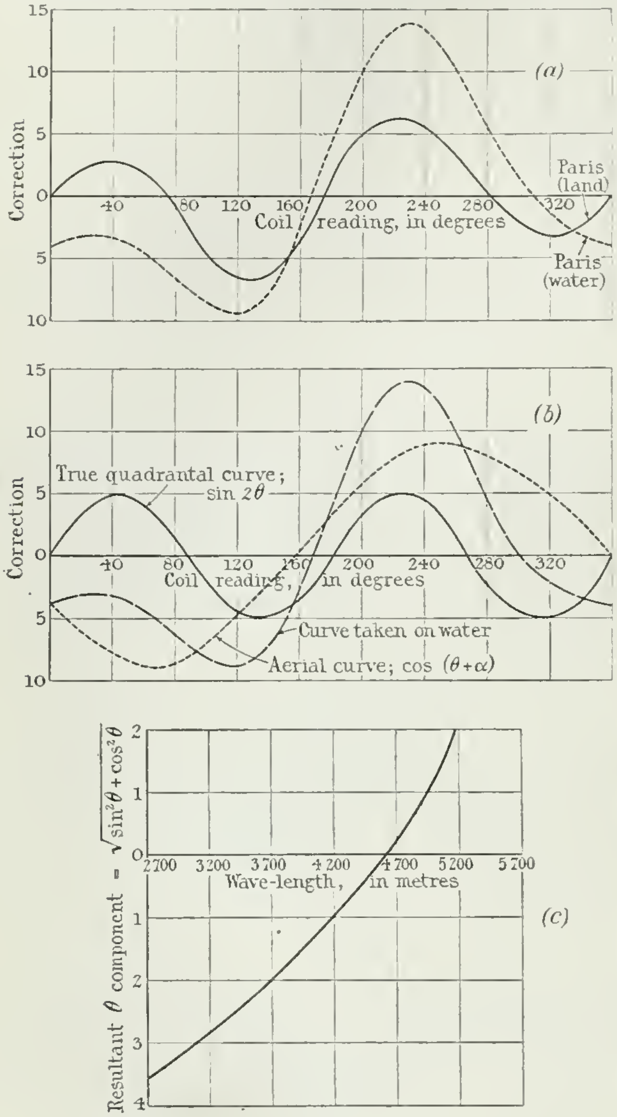


FIG. 7.

Fig. 7 (*b*) shows the analysis of the quadrantal error curve, for water.

The Handley Page machine under test was overhauled to find any possible places where change of resistance could take place, and it was decided that the most likely place was at the pin joints where the bracing wires are joined to the struts. These joints were short-circuited by short lengths of copper wire and the machine was again swung for quadrantal error, with the results shown in Fig. 6, which should be compared with Figs. 3 and 4. It will be seen that the curves are much more regular and do not change appreciably from day to day, although there is still a change with change of wave-length. The machine was flown in the interval between the taking of the curves of Fig. 6. When using this "metallized" machine, bearings taken in the air were satisfactory.

The effect of the bonding is to ensure that the resistance of the metal work does not change due to the vibration in flight causing variable electric contacts at the pin joints and thus changing the current paths in the metal work.

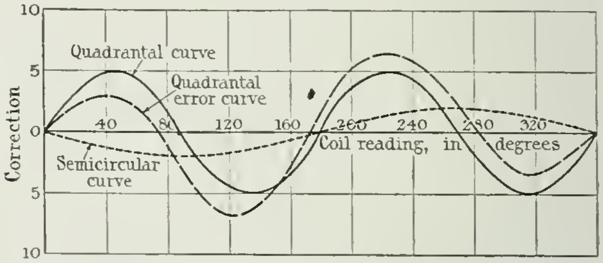


FIG. 8.—Analysis of quadrantal error curve, for land.

Table 1 gives values of true quadrantal error components for different wave-lengths taken on a "metallized" aircraft.

TABLE 1.

| Wave-length | Quadrantal component |
|---|---|
| m | |
| 5 200 | 5·5° |
| 3 900 | 5·35° |
| 2 700 | 5·2° |

EFFECTS OF METAL WORK ACTING AS AN AERIAL.

Further, it was found that when an aircraft is swung on the ground the capacity will be affected by the proximity of buildings and the height of the aircraft above ground. This is especially the case with seaplanes and flying boats, due to the sea being such a good conductor.

The metal work of the aircraft may be connected to the ground or water, or a large capacity to earth may exist when the aircraft is on the ground, so that the metal work acts as a straight-wire aerial. In this case as the aircraft is swung round the variation in induced voltage is a function of $\theta$ and not of $2\theta$.

Fig. 7 (*a*) shows curves taken on land and on the water for the same aircraft and on the same station (Paris). An analysis of the water curve Fig. 7 (*b*) shows a sin $2\theta$ curve and a cos $\theta$ curve out of phase with the $2\theta$ curve by 120°. Thus the metal work of the aircraft is acting both as a coil and as an aerial. The "aerial" effect is due to the very large capacity to earth when afloat, this capacity being very much reduced when the aircraft is mounted on a trolly on land.

Fig. 8 shows the analysis of the quadrantal error curve taken when the aircraft was on the trolly on the land and thus raised above the water. It will be noted that the phase values and amplitudes of the curves are different, this being due to the effect of the proximity of the sea water on the receptive qualities and electrical capacity of the metal work when the aircraft was afloat. Thus it will be seen that the error curve must be taken with the aircraft raised from the ground sufficiently to reduce the "aerial" effects to the same values as those obtained in the air. These curves can be split up still further to give fore-and-aft and athwartships components. In fact, by treating them like the compass deviation curves we can get the A, B, C, D, etc., components.

Table 2 gives the values of the "aerial" effects of the metal work split up into two components corresponding to the B and C components of the compass deviation. These give the sin $\theta$ and cos $\theta$ components of the correction curve for different wave-lengths.

TABLE 2.

| Wave-length | Components | |
|---|---|---|
| | sin $\theta$ | cos $\theta$ |
| m<br>2 700 | $-3\cdot6°$ | $+0\cdot7°$ |
| 3 900 | $+0\cdot77°$ | $-1\cdot5°$ |
| 5 200 | $+1°$ | $+2°$ |

The complicated structure of the metal work of an aircraft gives many aerials in parallel, each aerial circuit having different constants. Thus for different wave-lengths we get not only different current values in the metal work but also different current distributions. We cannot represent these varying current distributions by splitting up the "aerial" effects into sin $\theta$ and cos $\theta$ components, since the resultant *LS* value of the aerials are fictitious and do not represent the actual values, although the resultant effect shows a regular change with wave-length [see Fig. 7 (*c*)].

The components shown in Table 2 indicate that the equivalent aerials must have natural wave-lengths of the order of 3 000 m, and that the cos $\theta$ component has two wave-lengths between 2 700 m and 5 200 m at which the error is zero. This would appear to be impossible if an equivalent aerial is producing this component, i.e. the change of the value of the components with wave-length is erratic.

The only method, then, which can be used to predict the errors due to this aerial effect for aircraft of a particular type is to swing one machine, analyse the error curve, and assume that the errors on any one wave-length are constant for all aircraft of that type. That this is feasible is shown by Table 3, which gives the components for different aircraft on the same wave-length, viz. 2 700 m. It will be noticed that they are practically identical. Further, the maximum values are not large and therefore do not affect the resultant errors very considerably.

TABLE 3.

| Wave-length | Machine 1 | | Machine 2 | |
|---|---|---|---|---|
| | B | C | B | C |
| m<br>2 700 | $-2\cdot8°$ | $0\cdot15°$ | $-3\cdot5°$ | $-0\cdot5°$ |

*Non-varying errors.*—In addition to the errors mentioned above we have a component which does not vary with the angle of incidence of the wave. This corresponds to the A component of the compass deviation, and may be due to bad adjustments in fixing the directional wireless aerials, scales, pointers, etc., and to the aerial acting as an ordinary vertical aerial. In that case the component will have the same values for any angle on which bearings are taken.

Table 4 shows that the component varies with different transmitting stations. An error in taking the bearings from the chart when swinging the machine on known stations will give a non-varying error which varies with the station but not with wave-length. Further, any mutual induction or capacity which may exist between the main and auxiliary coils will cause an "A" component varying with wave-length.

Another source of this error is the apparent movement of the transmitting station which varies with the time of day. This is further referred to later in the paper.

TABLE 4.

| Station | Component A |
|---|---|
| Poldhu | $-2°$ |
| Chelmsford | $-0\cdot6°$ |
| Paris | $+0\cdot8°$ |

From the above considerations it will be seen that the errors for a machine of a given type can be predicted, except in so far as the non-varying component may vary from machine to machine and from station to station. This variation can be found approximately by swinging the machine once on a given station, since the variation from station to station is not very large in this part of the world, although it may be serious in the tropics.

*Correction of quadrantal error.*—With all these distorting effects the curves of error are rarely pure curves; also the errors are frequently large so that it is easy to make mistakes of one or two degrees when taking bearings and applying corrections. It will be of advantage, then, to have some means of reducing the errors to small values as is done in compass work. This can be accomplished by means of a quadrantal error corrector. One form consists of a coil capable of picking up energy from the incoming signal and so arranged that a voltage which just neutralizes the voltage induced by the currents in the metal work is induced in the directional wireless apparatus by the currents in this coil. The circuit is arranged as shown in Fig. 9. The loop aerial C is arranged so that a voltage may be induced in it from the incoming signal. This coil is placed near the auxiliary coil A of the direction-finding apparatus and is connected to a variable condenser. The aerial circuit consists of a rectangular coil of 12 turns of rubber-covered wire, the sides of the coil being 4 ft. by 3 ft.

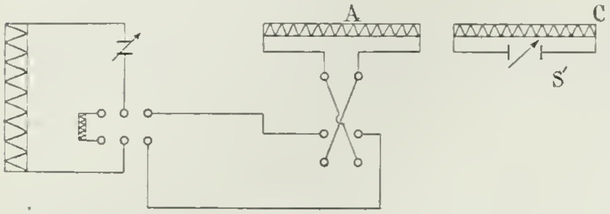


Fig. 9.

When undamped waves are incident the error produced by currents in the circuit is given by

$$\tan \alpha' = \frac{\omega M'_{max.} K' \sin 2\theta}{2Z'} \quad . \quad . \quad . \quad (10)$$

where $M'$ is the coefficient of mutual inductance between the coils C and A; and
$Z'$ is the impedance of the circuit CS.'

If this angle $\alpha'$ is equal and opposite to the angle $\alpha$ produced by the metal work there will be no error in the observation of the bearing. Whether $\alpha'$ is opposed to $\alpha$ or not depends on the phase relationship between the voltages induced in the auxiliary coil by the metal work and by C. This relationship can be adjusted by means of the variable capacity $S'$, which alters the angle of lead or lag of the current in C, and therefore the phase relationship of the induced voltage in A.

Thus, knowing $\alpha$, the quadrantal error, $\theta$, the angle of incidence of the wave, $\omega$ $(= 2\pi f)$ of the incoming signal, $L'$, the inductance and capacity for the circuit C, and taking $Z' = [\omega L' \sim 1/(\omega S')]$ we can find $K'M'_{max.}$ Calling this a constant we can calculate the capacity $S'$ required to neutralize the quadrantal error at all points of the quadrantal error curve.

When the curve is a pure sine curve $S'$ will obviously be a constant, since $\alpha$ varies as $\sin 2\theta$, but when the curve is distorted $S'$ must be varied as the angle $\theta$ varies. This can be arranged by driving a selector switch from the rotating directional wireless aerial so that the correct value of $S'$ is inserted for a given angle of incidence of the wave.

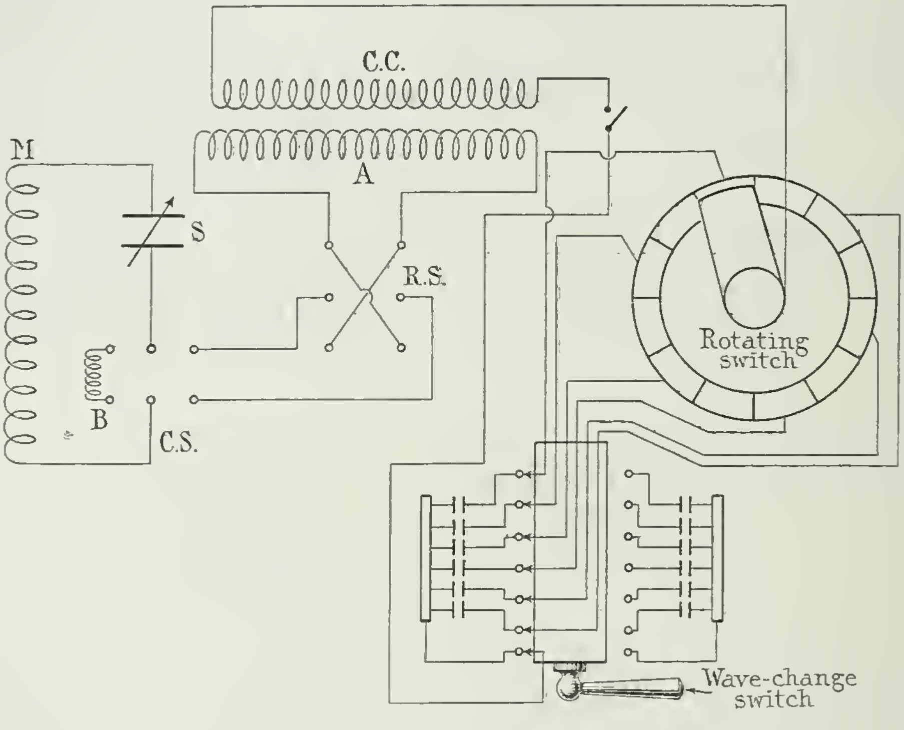


Fig. 10.

In practice even with very distorted curves the errors are negligible when correction is made at five or six selected points on each wave. We thus require a separate set of condensers for each different wave-length we wish to receive when very distorted quadrantal error curves are obtained, so that, just as we insert correcting magnets in the case of the magnetic compass, we insert condensers in the correcting circuit for the wireless compass. The complete apparatus is then as shown in Fig. 10.

The curves in Fig. 11 show the effects of using a corrector coil with one value of capacity, the plain curve being obtained with no corrector and the dotted curve with the corrector switched in.

Further, Fig. 12 shows the relationship between the correcting capacity and the angle of incidence of the wave. The capacity will be seen to vary very slightly over a large variation in angle of incidence of the wave; hence the possibility of correction with very few capacity values.

### WAVE DISTORTION.

When the incoming wireless wave is distorted, due either to heavy loading of the transmitter or to the surface over which it is propagated, the currents set up in the metal work will not be pure sine waves but may be made up of a fundamental sine wave together with one or more harmonics. The quadrantal error is then due to the sum of the effects produced by the fundamental and the harmonics, so that the equation for the quadrantal error becomes :—

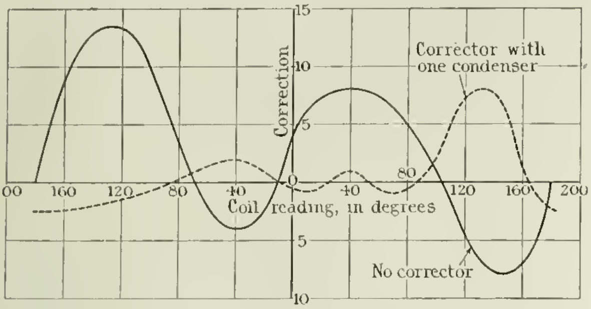


FIG. 11.—Effect of quadrantal error corrector.

$$\tan \alpha = \omega MK\left\{\frac{1}{Z_1} + \frac{2}{Z_2} + \frac{3}{Z_3} \ldots\right\} \quad . \quad (11)$$

The effect of the harmonics on the quadrantal error may be very large, especially if the metal-work circuit is in resonance with any harmonic, since $1/Z_x$ will then be small.

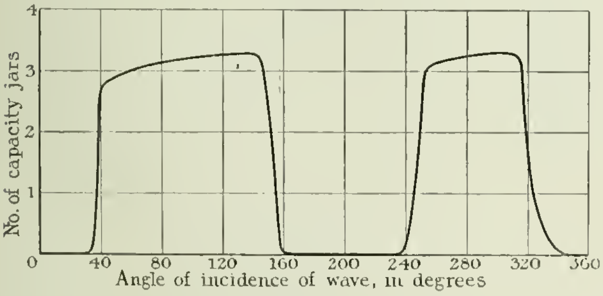


FIG. 12.

The effect of signals from very heavily loaded aerials is shown in Fig. 13. These aerials were used in small beacon stations having a power of 2 kW and transmitting on a wave-length of 2 300 m. The aerials were small, the height being 120 ft. and the span 200 ft., hence the inductance loading was very high, giving a very distorted wave.

To sum up, it is necessary, in order to get the best results, to metallize thoroughly all machines and swing them well away from the ground or any earthed objects. The quadrantal error can be neutralized by the use of a corrector coil connected in series with a variable condenser and magnetically coupled to the directional wireless aerial so that the voltage induced in the auxiliary coil of the set by the currents in the metal work is wiped out by the voltages induced by the corrector coil.

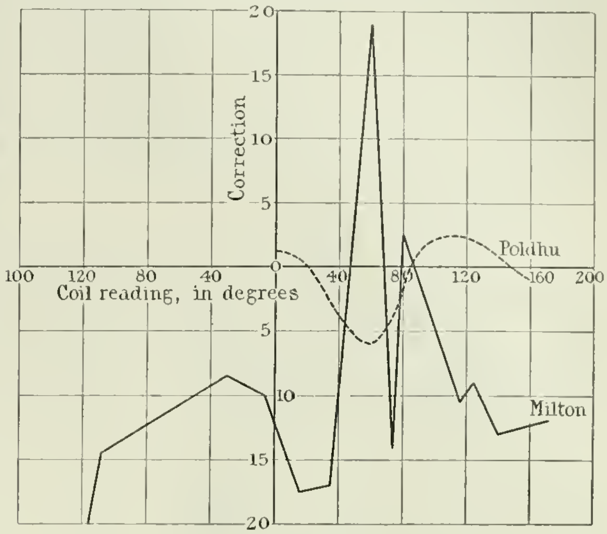


FIG. 13.

### DAILY VARIATION IN DIRECTIONAL WIRELESS BEARINGS.

When using directional wireless to obtain bearings of fixed ground stations it has been noticed that the bearings are not constant, but appear to change during the course of the 24 hours. The change is sometimes well defined, varying with the time of day more or less in the form of a sine wave, but more often the curve follows no definite laws, only sharp variations being obtained (cf. Figs. 14 and 15). The variation observed is not very large, being of the order of 2° or 3° in this part of the world, but even this may cause large errors in position-finding when the fixed station is several

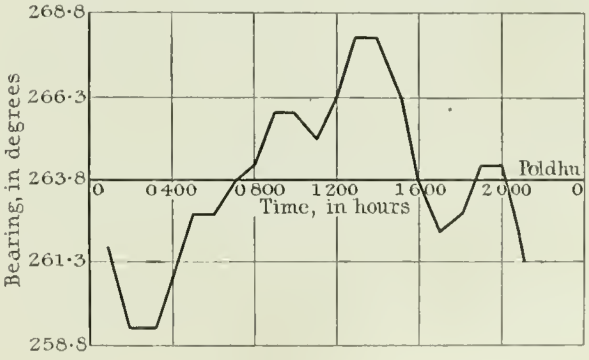


FIG. 14.

hundred miles away. It is therefore important to try to find the cause of the variation in order that corrections can be made for navigation purposes.

The following are the possible causes of variations :—

(1) Local errors at the receiving station which may vary with the time of day, e.g. moisture on a mass of trees near the receiving aerials.

(2) Errors due to the nature of the country over which the wave has passed, e.g. whether sandy or wet, whether metalliferous near the surface, etc.

(3) Refraction when passing a coast line.

(4) Continuous refraction during the whole passage of the wave.

(5) Reflection from some moving surface, such as the day and night shadow line.

Cause (1) may be detected by taking observations from different stations separated by considerable distances so that the results with different surroundings can be compared. This has been done (see Figs. 15 and 16) and it will be noticed that the variations are similar although the readings for Fig. 15 were taken in the middle of a dry, open parade ground, and those for Fig. 16 in a marshy, open meadow. Thus (1) would appear to be ruled out as causing the variation.

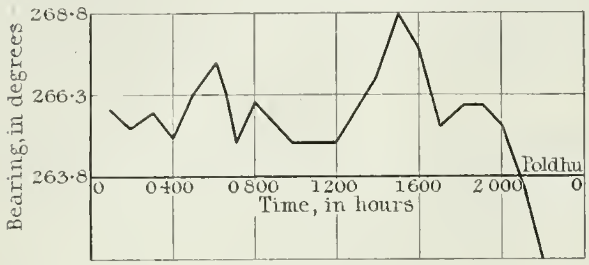


FIG. 15.

The nature of the country between the transmitting and receiving stations may affect the wave, but this effect would be constant and not change with the time of day, since the character of the land or water will not change.

Coastal refraction may account for a varying effect since there may exist a sharply defined barrier on the two sides of which the atmosphere has widely different electrical properties. Thus over the sea the air is highly ionized as compared with that over the land. This ionization will change with the time of day, due to the action of the sun's rays and their reflection from the water.

The velocity of an electromagnetic wave can be calculated, according to Maxwell's theory, from the formula $V = 1/\sqrt{(\mu K)}$, where $\mu$ = permeability, and $K$ = dielectric constant, so that any change in $\mu$ or $K$ will cause a change in the velocity of the wave and therefore produce refraction. Due to the difference in ionization over the sea and land it is possible that the dielectric constant $K$ for the atmosphere over the sea is different from that for the atmosphere over the land.

It has been noticed, however, that the deviations occur even when no coast line intervenes, and also that stations situated to the northward of the receiving station had no variation with the time of day, but a constant deviation only. Stations east and west, however, did vary with the time of day (cf. Figs. 17 and 14 for Stonehaven and Poldhu respectively, these curves being taken at Farnborough).

It is well known that sunlight possesses great power of producing ionization in gases by action of the short wave-lengths on the molecules of gas. This power is called the photo-electric effect of light. Now consider two stations several hundred miles apart along a parallel of latitude. The sun rising at the easterly station begins to ionize the air, whilst the other station is still in darkness. As time passes, the ionization increases and extends to the westerly station so that a gradient in ionization is established between the two stations. Later in the day the sun is more powerful at the westerly station, whilst re-combination of the electrons and the ions has commenced at the easterly station, so that the gradient is eventually reversed and becomes easterly instead of westerly.

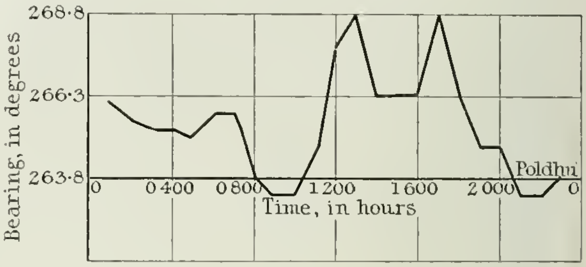


FIG. 16.

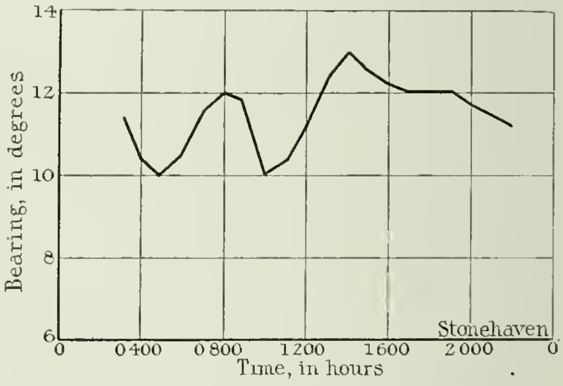


FIG. 17.

The positions of maximum and minimum ionization travel round the earth following the sun, causing a continual change in the ionization gradient between two stations on a parallel of latitude. We have just seen in connection with coastal refraction that the dielectric constant of the air may be affected by the amount of ionization. The ionization gradient will produce a gradient in the dielectric constant, which would cause a wireless wave travelling along a parallel of latitude continually to change its velocity, thus giving rise to continuous refraction.

We can account for the permanent deflection of stations due north and south in the following way:—

Stations on a north and south line will have a definite ionization gradient from the equator to the poles, since the light waves must penetrate a greater distance through the air to the more northerly stations. The ionization will thus be greater at the equator than at the poles. This gradient does not, however, change with the time of day, so that we get a permanent deflection. When a wave is travelling in a north-easterly direction, say, it will be under the influence of both gradients and the result will be the vector sum of the individual deflections. The upper portions of the wave then being refracted, the whole of the wave is refracted, the upper portion to a far greater extent, however, than the lower portion nearer the ground. An analogous case is the effect of rivers and good conducting layers in the earth's surface deflecting wireless waves from their true path.

The effects of changes in the ionization of the atmosphere will be to produce changes in the deflection of the wireless waves, so that although a general change in deflection may take place varying with the time of day, sharp variations may also be experienced, being produced by varying atmospheric conditions, especially variations in the upper atmosphere. The deflections may be expected to be large and subject to sharp variations in equatorial regions, due to the large amount of ionization taking place, and also in polar regions, due to the concentration of ionization at these points.

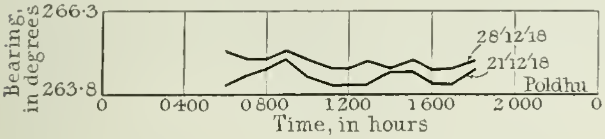


FIG. 18.

In addition to the daily variation in wireless bearings we should, if our theory is correct, expect to find an annual change in the variations due to the different gradients produced in winter and summer. That this is the case may be seen by comparing Fig. 18 (showing curves taken in December) with Figs. 14 and 15 (showing curves taken in September) on the same station (Poldhu). It will be noted that the variation in December is very much smaller than that experienced in September.

When directional wireless work is carried out in equatorial regions, it will be of great importance to investigate the deflections produced, and it would seem that the best method of attack would be to study the effects of ionization of the atmosphere, expecially at high altitudes. Existing meteorological stations could be used for this purpose, and when reliable formulæ had been deduced from observations, forecasts could probably be made by means of which it would be possible for navigators using directional wireless to correct their bearings.

The last possible cause of variation in bearing is the effect of reflection from the daylight-night shadow line (see Fig. 19). This would cause stations due north of the receiving station to vary more than stations due east and west during the day, because the angle of reflection would vary continuously for stations north and south, but would not vary for stations east and west, the wireless waves being incident normally on the shadow line, whilst the waves from the stations north and south are incident at angles which might cause reflection.

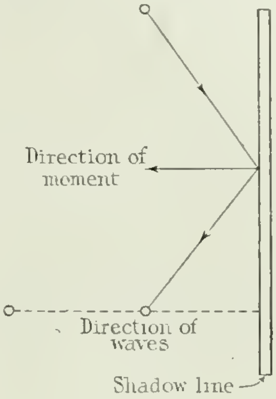


FIG. 19.

It is found, however, that stations on an east and west line vary more than stations on a north and south line, showing that reflection from the shadow line cannot produce the variation observed.

# TRANSOCEANIC WIRELESS TELEPHONY.

### By Dr. H. W. Nichols.

(*Lecture delivered before* The Institution, *22nd February*, 1923.)

I think that many of the members know that the American Telephone and Telegraph Company and the Radio Corporation of America have, for the past two or three months, been carrying on investigations to determine signal strength and other important data which will allow us ultimately to engineer a transatlantic radio telephone circuit, if this be desired. I hope that members will forgive me if a good deal of what I say to-night is somewhat elementary; I want to be sure that they know exactly what is meant by some of the terms and phrases which have grown up in the past seven or eight years in connection with this art.

In order to introduce the subject as easily as possible, I should like to ask members to consider, first of all, a very simple type of telephone circuit, namely a circuit consisting of a line, a microphone, a battery and a receiver, all in series. This is shown in Fig. 1, in which *a* represents a telephone line, which, of course, is not the simple thing it is represented to be by the two wires. It has attenuation, and, ordinarily, the current at the sending end is greater than that at the receiving end. *b* is a battery which sends a direct current through this circuit. I shall refer to this current as the "carrier" current; it is constant. *c* is a microphone, the function of which is to vary the amplitude of the otherwise steady current. It does what we call "modulate" the carrier current. *d* shows the simplest type of telephone receiver, consisting of an electromagnet with a diaphragm on which the magnet can operate. All this, of course, sounds very simple, but it is important that we run over it. When the microphone is operating, the otherwise constant amplitude of the carrier current is varied slightly. The result is that there flows through the telephone receiver a current which is made up of two components, the first being the constant carrier current or something almost exactly equal to it, and the second the signal, the variable ripple superposed on the carrier.

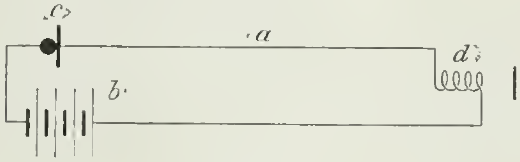


Fig. 1.

The telephone receiver itself, being an electromagnet, gives a deflection proportional to the square of the current flowing through it. This is indicated by the following formula:—

$$(I_c + I_s)^2 = I_c^2 + 2I_cI_s + I_s^2$$

If $I_c$ represents the constant carrier current, and $I_s$ the signal, the force on the diaphragm of the telephone receiver is proportional to the square of $I_c + I_s$, which is, of course, made up of three terms, namely $I_c^2$ (which is constant, because $I_c$ is constant), the middle term $2I_cI_s$ (this is directly proportional to the signal, which is what we want to get) and $I_s^2$, which is proportional to the square of the signal and consequently of double frequency, because any periodic function squared gives a constant and a double frequency component. Consequently we do not want the third term.

If speech is to be of good quality in the receiver, the $I_s^2$ term must be small compared with the $2I_sI_c$ term; in other words, the carrier must be rather large compared with the signal, and this condition does obtain in the case of a simple telephone circuit of this kind.

This kind of circuit possesses two or three disadvantages which apply also to the radio circuit, and that is my only excuse for referring to it. In the first place, it will be noticed that the circuit requires that the battery should send current through the line. Now the battery current, i.e. the carrier current, contains no element whatever of signal, and consequently there is no need to transmit the direct-current carrier from the transmitting end to the receiving end, except as a means for producing this middle term, $2I_cI_s$, at the receiver. The transmission of the carrier current through the line, therefore, involves an unnecessary loss of power. This is one disadvantage.

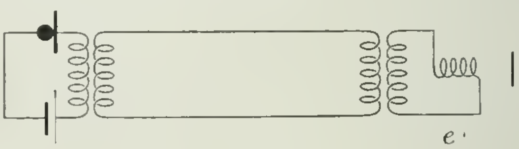


Fig. 2.

Another disadvantage is this. This line, being an actual telephone line, will have both its attenuation and impedance varying with weather and other conditions. Now, if the characteristics of the line vary, then, since the carrier is transmitted from the transmitting end, both $I_c$ and $I_s$ in the middle term of that last expression will vary, and consequently we shall get the variation factor in the received signal squared, instead of to the first power.

The first obvious improvement on this simple system is shown in Fig. 2. This differs from Fig. 1, in that two transformers have been introduced. The first transformer restricts the carrier current to the transmitting apparatus, because that is the only place where it is needed. The variations in this carrier current go through the transformer and to the receiving end. At the receiving end, if we receive in the manner shown by this figure, we shall get only double-frequency signals, that is, we shall not get intelligible signals, because the only thing that appears at the receiver is the $I_s$ term. In order to make the signals intelligible at the receiving end, it is necessary to reintroduce the carrier current $I_c$, which, of course, in practical telephone apparatus is done either by putting a battery at $e$ or by placing a permanent magnet in the telephone receiver. This change restores the conditions which existed at the receiving end under the conditions indicated by Fig. 1.

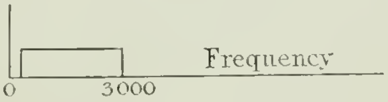


FIG. 3.

In Fig. 3 I have plotted as a spectrum the distribution of currents which must be passed by the line. It is well known that, in order to transmit intelligible speech, a range of frequencies of something like 3 000 periods is required. The microphone generates, and the line must transmit, a spectrum represented roughly by the rectangle on the left of the figure.

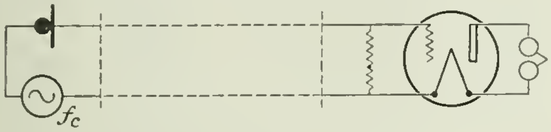


FIG. 4.

So far I have endeavoured to bring out, first the meaning of "carrier," and secondly, the fact that the carrier does not contain any element of signal and need not be transmitted to the receiving station. There are, in fact, real advantages to be gained by not transmitting it.

In Fig. 4 I have shown exactly the same kind of circuit, except that the carrier current is now an alternating current of frequency $f_c$, delivered by the alternator. In other respects the transmitting end of the circuit is exactly the same. The microphone modulates the alternating carrier current, and the result of that modulation—the result of varying that alternating current's amplitude in accordance with speech—is to produce a spectrum represented by $S_1$, $f_c$ and $S_2$, as in Fig. 5. There is a carrier frequency component $f_c$, and then there is a band, called the upper side band, extending up to the carrier frequency plus 3 000 periods; also there is another band, called the lower side band, extending down to the carrier frequency minus 3 000 periods; in other words, the effect of modulating an alternating current carrier by speech is to produce a spectrum twice as wide as the band which it is necessary to transmit.

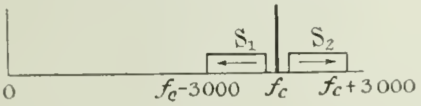


FIG. 5.

At the receiving end is shown a device which functions in a similar manner to the telephone receiver; that is to say, currents in the output circuit of the tube are proportional to the square of the voltage applied across its input terminals. This means that the tube conditions are so arranged that if we apply a sine wave to the grid circuit we shall get a current of double frequency in the output circuit.

Exactly the same remarks apply to this circuit as to the simple telephone circuit. There is transmitted over the line a current having a spectrum as shown in Fig. 5. The carrier component has no element of signal in it, and there is no need to transmit it over the line. If we do, then the effects of variations in the line will be squared in the receiving circuit, and, furthermore, we shall use much more power if we transmit the carrier than if we do not. There are two very important advantages, therefore, to be derived from excluding the carrier from the line itself.

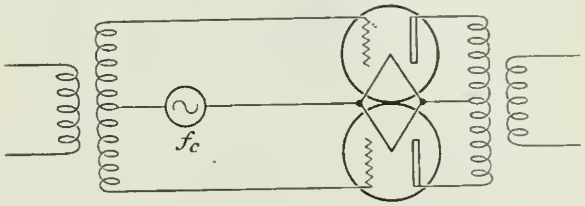


FIG. 6.

In order to exclude the carrier current, the device shown in Fig. 6 is used. There are, of course, other ways of effecting the same result. The carrier current is generated by means of the alternator shown in the middle of the figure, and the speech which is to modulate this carrier current is applied at the left. If this circuit is examined, it will be seen that if no speech is being applied, and if the tubes and transformers are quite symmetrical, the carrier current will produce no effect whatever in the output circuit of that system, because currents will flow down in the upper part of the transformer winding, and equal currents will flow up in the lower part of the winding. As soon as we begin to speak, however, the tube will be unbalanced, and we shall secure an output proportional to that unbalance, and the peculiarity about the output is that there will be no carrier-frequency component present. That is shown by the spectrum indicated in Fig. 7.

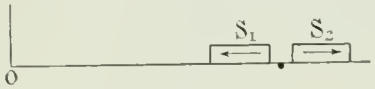


FIG. 7.

Instead of getting the original spectrum, as in Fig. 5, we shall get a new one which contains only one-third of the power of the original one but still contains all the elements of the signal. The two side bands are exactly alike; we do not even need to transmit both of them. If we transmit only one of them, we shall still have all the elements of signal which were present in the speaking voice, so that by means of electrical filters we can cut out all but, let us say, the upper side band. In the receiving end, in exactly the same way as before, if we apply the side band directly to the receiving tube we shall get in the output circuit of that tube a signal which is unintelligible, because it is proportional to the square of the input. Consequently it will be of double frequency. However, if at the receiving station we introduce again the carrier component in exactly the same way as we did in the case of the simple telephone circuit, and then square the result—that is, detect the signal—it can very easily be seen by the binomial theorem that we shall get exactly the same condition as before, i.e. one component directly proportional to the signal, and that is what we want to get.

Time will not allow me to discuss exactly what happens in detection. In general there will be developed in the output circuit frequencies which contain all the possible combinations that can be secured by addition to and subtraction from all the impressed frequencies. Just one word more on this. The effect of transmitting only one of these side bands, if it were due to a simple sine wave, would be that we would use only one-sixth the amount of power in the complete modulated wave.

So far I have been talking about wires. The only difference between wire transmission and radio transmission is in the medium used for it. Radio transmission must, of course, take place through what is known as the ether; the ether differs considerably from a conductor, and is very much more like a condenser than a copper wire. Consequently, in order to get signals through it, it is necessary to use rather high frequencies, because low frequencies cannot be transmitted. Another difference between the ether and a copper wire is that the ether forms, as it were, a common circuit connecting every one. Unless directional methods of transmission or reception are used, the only way in which we can discriminate between channels in the ether is on the basis of frequency. There is another and very important difference between the ether and a copper wire, i.e. that its transmission characteristics are very much more variable than is the case with a wire circuit. There is a tremendous difference, for example, between day and night transmission; there is a large difference at different times of the day; and, what is still more annoying, there is a variation going on from minute to minute, or from second to second almost, especially with short wave-lengths, which it is very difficult to take care of.

With that introduction, I should like to mention what factors are important in the design of a long-distance radio telephone circuit—as I see them, of course. In the first place, it is necessary to use rather long waves. The reason for this I shall bring out when I come to discuss the measurements which we have made. In the second place, it is obviously necessary to secure as great an economy in power as possible, because the powers involved in transoceanic telephony are likely, in the summer time, to amount to 1 000 kW. In the third place, it is extremely important not to use any wider frequency-range than is necessary. I have already mentioned that a frequency band of about 3 000 periods is required to transmit the human voice with good quality, and even more is needed to transmit music with good quality. We cannot transmit more than one channel in a given frequency-range in the same direction.

The range of wave-lengths available for transatlantic communication is at present fixed by the London Convention, and probably will not be changed very much in the near future. The range of wave-lengths available is from 8 000 m upwards. Now, 8 000 m is equivalent to 37 500 periods, and about the greatest wave-length that we are likely to use in the immediate future will be about 30 000 m, equivalent to 10 000 periods. That is to say, there is available for transatlantic communication a frequency-range of 27 500 periods. We can use that, and we want to use it in the most efficient manner possible. Suppose we wish to use it for telephony. If we modulate in the usual way we shall produce a carrier and two side bands, each of the latter being 3 000 periods wide, making a total of 6 000 periods which must be transmitted. Using that 6 000 periods, in the 27 000 odd periods available, we can only have four telephone channels. What is worse, if we do that we cannot allow any telegraphic communication at all, because that frequency-range will already be used and there are 20 or 30 telegraph channels to be taken care of. It will be seen, therefore, that it is extremely important to use as few periods as possible in this transmission.

For that reason I think that for transatlantic communication by radio-telephony, it is essential to transmit only one of the side bands. In that way we multiply the possible number of channels approximately by two; or, in other words, we leave free for telegraphic traffic a very considerable range of frequencies, because we can operate approximately 10 telegraphic channels in the frequency-range required for one telephonic channel. We must not waste the frequency-range available in the ether for telephony by transmitting the complete modulated wave.

We have built up radio-telephony apparatus which conforms to our ideas of what such apparatus ought to be; it economizes in power by sending out only one side band and it occupies the minimum frequency-range by the same device. It is fortunate that those two conditions can be achieved by the same means. I am going to describe very briefly what this apparatus is, and then show some illustrations of it.

We commence by developing a modulated wave at very low power—of the order of 1 watt or less—employing vacuum tubes of the type used in telephonic repeaters. That is, we generate both side bands but not the carrier; the carrier is eliminated by the balanced modulator system shown in Fig. 6. Then by means of filters we cut out one of the side bands because both are not necessary, with the result that we have a fraction of 1 watt of single side-band high-frequency telephone current of about 55 000 to 57 000 periods. The next thing we do is to amplify this to about 300 watts by means of an amplifier consisting of three stages. From there it goes to another amplifier by means of which it is raised to a power level of about 5 kW. From there it goes to still another and larger amplifier, which is capable of raising the power to 200 kW but which, in the tests which we are running now, actually raises it to only 60 kW because that is all we need. From the final amplifier it is passed to an antenna, which in this case is one of the Radio Corporation's antennæ at Rocky Point.

There is one further argument in favour of this single side-band transmission, which is this: if we are transmitting at 60 000 periods we cannot design an antenna which will have a perfectly flat frequency characteristic 6 000 periods wide at 60 000 periods, that is, 10 per cent of the frequency. By sending only one side band it is necessary to have only 6 per cent of the frequency, over which the response is fairly uniform. Before I give any illustrations of the apparatus, there is one important thing to emphasize. This 60 kW which we have been using in our tests is just the same in its effect as approximately 250 kW or more of complete modulated wave as ordinarily produced.

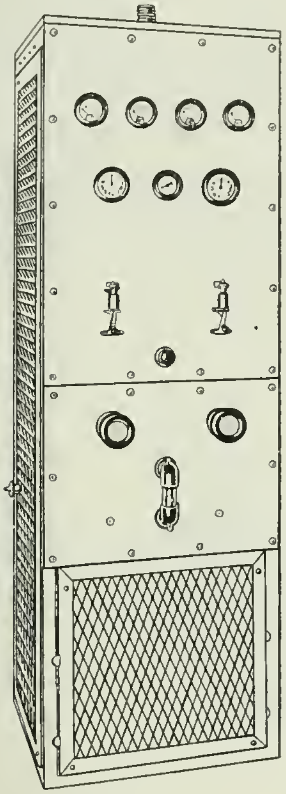


Fig. 8.

I am sorry that I have no drawings of the first stage in which the modulated wave is produced. Fig. 8 represents the front view of the 5 kW amplifier, which raises the power from 300 watts to 5 kW. At the top are meters for measuring the currents of each of the two water-cooled vacuum tubes which are inside. Two clocks will be noticed, one of which is arranged to operate only when the filament is being burned, the other when the plate voltage is applied. This gives a check on the life of the tubes; it is simply a refinement. In the middle is a thermometer by means of which excessive temperature-rise in the cooling water can be detected. We also have a filament alarm. In the middle of the panel are shown circuit breakers and rheostat handles for controlling the filament, also a glass inspection tube through which the water flows.

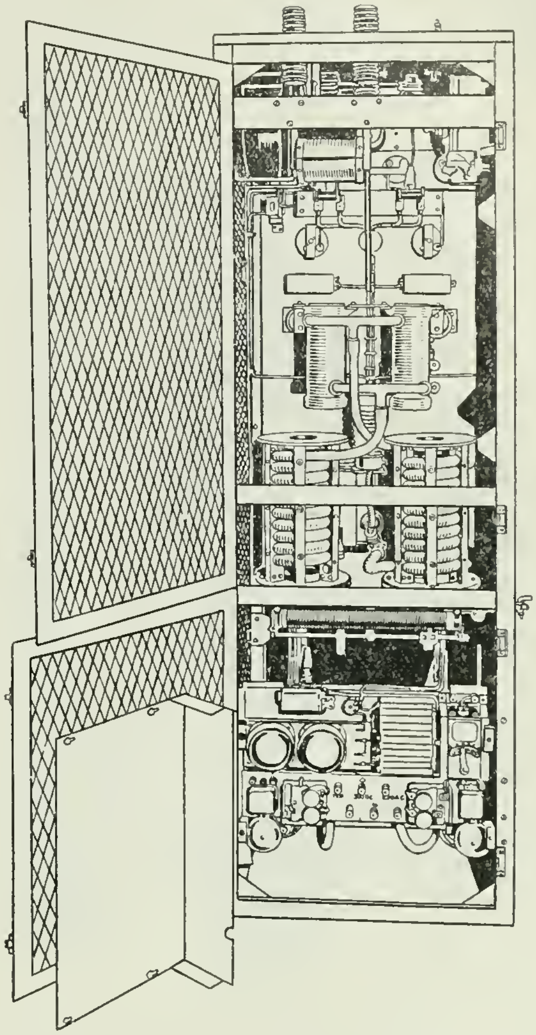


Fig. 9.

Fig. 9 shows a rear view of the same amplifier. The two cylindrical water jackets into which the vacuum tubes are fitted can be readily seen. Water flows through these and then through the hose, which is arranged in a spiral form; tap water is ordinarily used, although sea water could be used if desired. Only a small amount of water is required to cool the tubes, and the temperature is regulated by the flow of water. A water-flow alarm, which operates if the flow of water is cut off for any reason, is provided. The length of hose used is necessary to insulate the tubes from earth, as we are operating the anodes of these tubes (which are, of course, electrically connected to the water jackets) at from 6 000 to 10 000 volts above earth potential. It is, of course, much more convenient to operate with the anodes rather than the filaments at a high potential. The insulation between the water jackets and earth is the column of water in the hose.

Fig. 10 shows the vacuum tube that we are using. It consists of a copper anode to which is sealed the glass cylinder. This seal will hold a vacuum between − 190° C., the temperature of liquid air, and + 350° C., the boiling point of mercury. No trouble of any kind has been experienced with these copper-glass seals. Inside the anode is the grid structure, a helix, and inside that again the tungsten filament, which takes about 25 amperes. For heating the filaments we use alternating current taken from the secondary of a small transformer in the amplifier. The terminal bringing out the grid lead, and the cap mounting the filament terminals, can be clearly seen in the illustration.

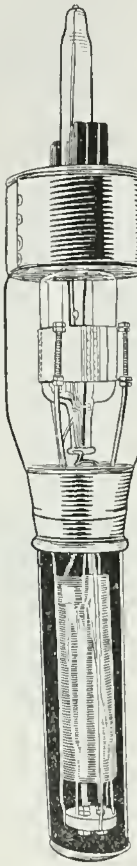


Fig. 10.

The amplifier shown in preceding illustrations raises the power to 5 kW. Fig. 11 shows one of the amplifiers which raises the power to its final level, and was prepared before the assembly was finished. There are 10 water jackets, mounted in two rows of 5. The hose serves exactly the same purpose as in the other amplifier, namely, to insulate the water jackets and the anodes from earth. The switches mounted on the front panel allow us to connect a meter into any one of the filament circuits of the tubes. Below the switches are filament adjusting rheostats. The whole assembly is mounted in an iron frame, the front of which is about the size of an ordinary door, of about 4 ft. in depth. Each of the tubes deals with 10 kW, and this device when used as an amplifier will amplify a sine-wave current to 100 kW. With two of these amplifiers in parallel, a capacity of 200 kW is, of course, obtained.

Fig. 12 gives a view of the same apparatus after installation at the station of the Radio Corporation at Long Island. The thermometer indicating the temperature of the cooling water can be seen at the top of the panel.

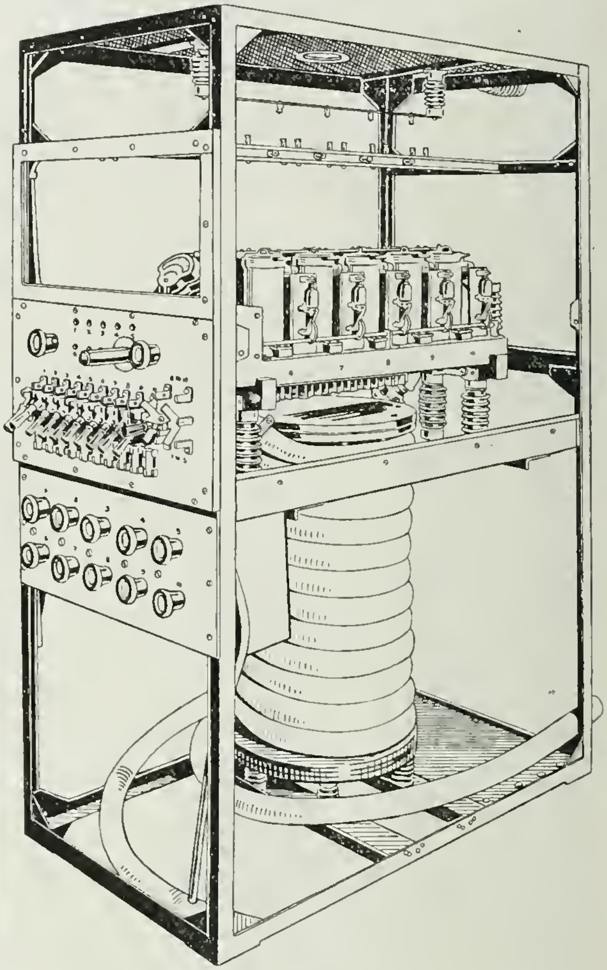


Fig. 11.

Fig. 13 is a side view of the same apparatus. In this view can be seen the device for controlling the flow of water and automatically shutting down the circuit if the water stops.

There is no illustration available of the apparatus used to receive this transmission, but it is extremely simple, consisting of a receiving set operating from a square loop comprising 50 turns of wire. The loop is earthed in the middle and is about 6 ft. square, the voltage being applied to the grid of the receiving tube from half the coil. The reason for this is, of course, that an ordinary loop is not only a loop but a vertical antenna, so that greater directional effect is obtained if we eliminate the vertical antenna part of the reception. That is done by making the two halves of the loop operate in opposite directions as far as vertical effect is concerned, and connecting the grid and filament of the receiving tube across only one half of the coil. This arrangement produces very sharp directional characteristics, as compared with the older method of using the full loop across the receiving tube.

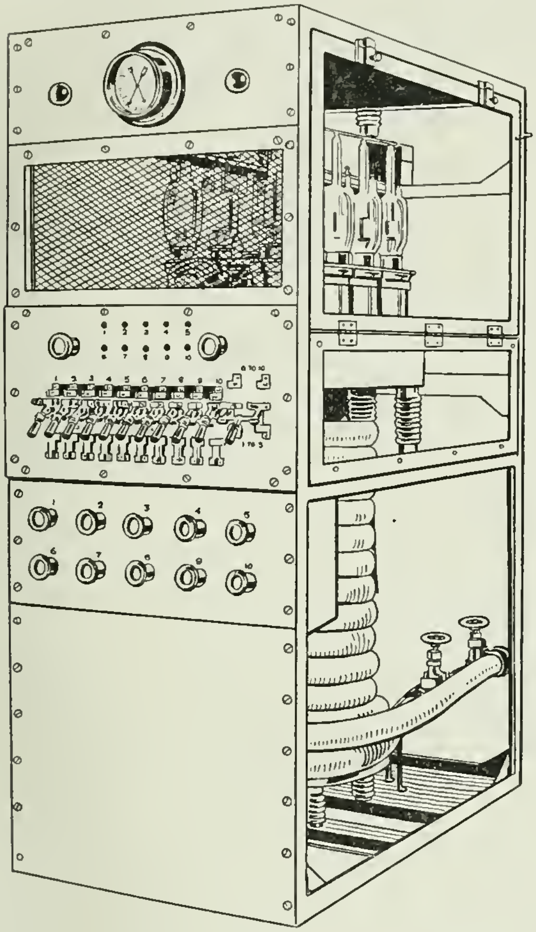


Fig. 12.

Now, what travels across the ocean is only one side band of this modulated wave. It has been explained by analogy that if we tried to detect this alone we should get unintelligible speech because all the frequencies would be doubled; therefore, before we attempt to detect this we must reintroduce the carrier-frequency component—we must reintroduce the first frequency that we generated at Rocky Point and then suppressed. The first step, therefore, is to make an oscillator to generate a current of the frequency which was eliminated at the transmitting end, and then to couple this to the receiving circuit. Rather special arrangements are made to amplify the incoming signal and, at the same time, to secure good filter action. Finally, the combination is detected.

On detection of the single side band and the carrier we get the original speech. Theoretically, the quality would be much better than would be the case if we transmitted both side bands without the carrier, because if we transmit both bands the two bands beat and interact with one another in the receiving set, and tend also to produce double frequencies. If, therefore, we can maintain the frequency of our local oscillator constant we can, as experience on open-wire " carrier " circuits in the United States has shown, get better quality than if we transmitted the complete modulated wave.

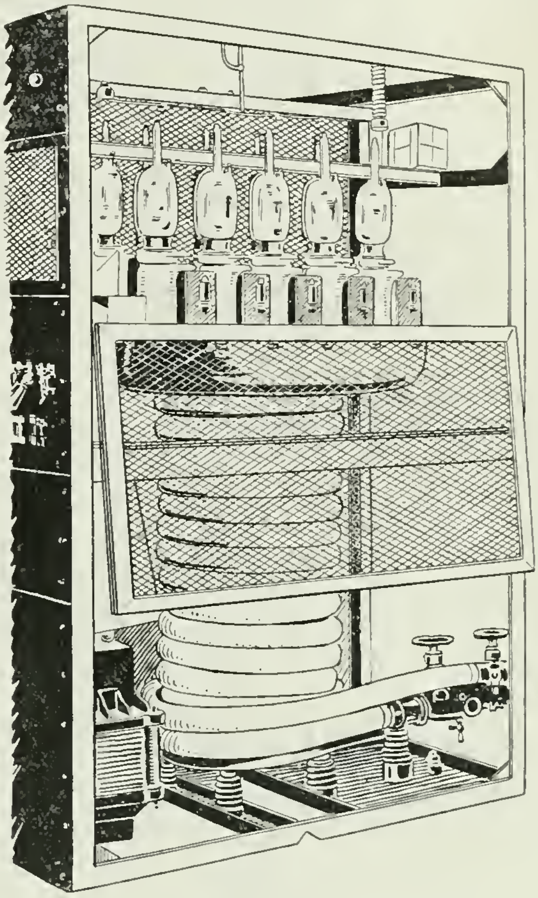


Fig. 13.

It is perhaps worthy of mention that this system of transmission, i.e. of sending out only one side band, is in commercial use in the United States on the carrier telephone circuits. It is used there not to save power, because in the case of land lines this is not of great importance, but to cut down the cross-talk, which would otherwise be caused by the powerful carrier component, and also to secure a greater number of conversations in a given frequency-range, because on an ordinary open-wire circuit there are also available only about 30 000 periods.

After detection in the receiving set, the resultant output of the detector is then, of course, amplified as much as may be necessary. This depends on what we are going to do with it.

The receiving set used was built primarily for another purpose: it was set up at New Southgate in order to make measurements of the strengths of signal received on this side, and also of the noise—the unavoidable electrical disturbances always present at every receiving station.

Now, in engineering any communication system whatever—whether radio or wire or speaking tubes, etc.—in order to secure intelligible speech at the receiving end it is absolutely essential that the strength of the signal received should be greater—perhaps 10 or 15 times greater—than any noises which arrive at the receiving station. It is perfectly obvious that if we get only a very weak signal—perhaps only a little louder than the noises—it is of no use whatever to amplify, because we amplify the noises as well. It is useless to amplify a weak signal, unless the noise level is so much below the signal level that the result will be intelligible.

The first step, therefore, in the intelligent design of a transatlantic radio-telephone circuit, is to determine how much signal we get over here per kW in New York; and secondly, how much noise we get. If we secure data of this kind over one year (which is about the cycle for noise and also for transmission) then it is, of course, a very simple matter to determine how much power we must have for every day in the year at New York. If we know that, we can find out how much it costs, and then we can tell whether it is commercial to do it. No one can tell before that. The first step, therefore, in the design of such a system is to secure this fundamental information.

For the purpose of measuring the noise we make use of the receiving loop and compare the signal coming

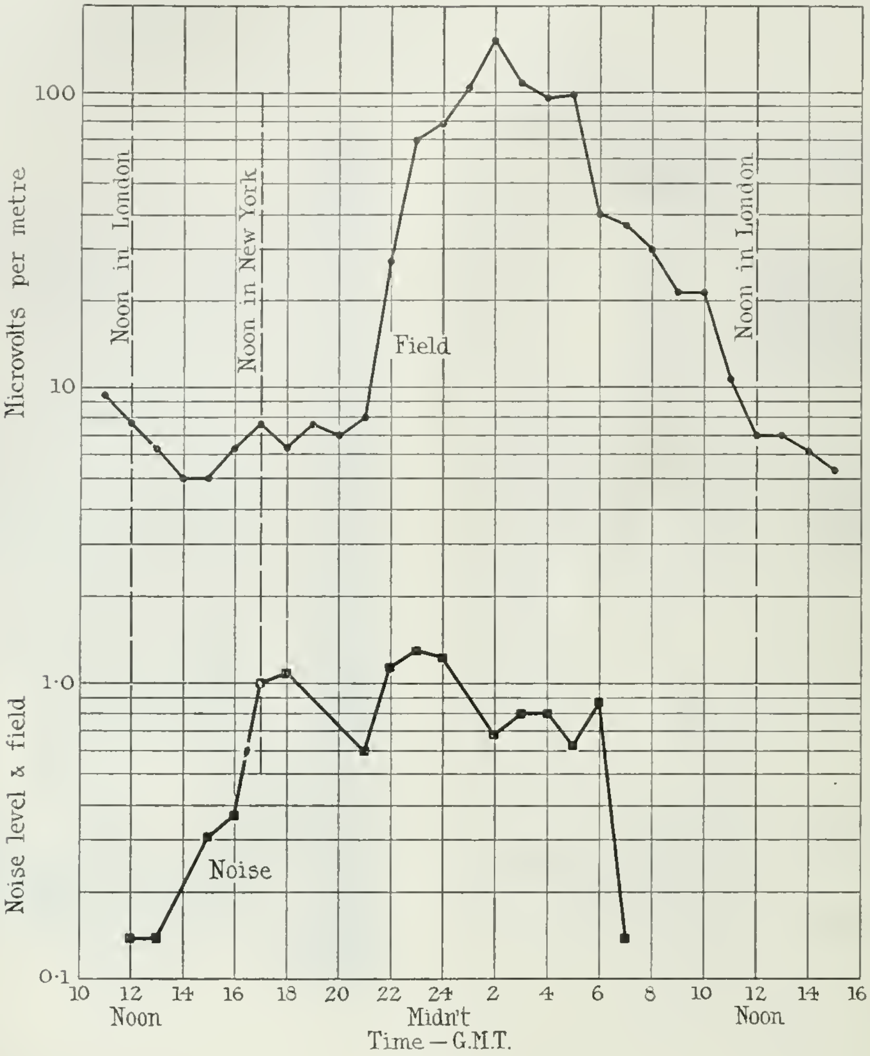


Fig. 14.

in with a known signal which we introduce. Fig. 14 gives some of the results of these determinations. What we want to measure at the receiving station is electrical force or electrical intensity. We want our results to be independent of the kind of antenna used, so we measure the electric field strength in the ether just outside the antenna. The normal unit for this is volts per centimetre, but this unit is rather inconvenient and accordingly we use microvolts per metre, that is, absolute or C.G.S. electromagnetic units. The results plotted in Fig. 14 are in terms of microvolts per metre in the ether. It is necessary to remember, in examining this curve, that a logarithmic scale is used for the field (ordinates); there would otherwise not be room to plot them on the paper. The times indicated are Greenwich mean time. The upper curve represents the strength of signal which we get about this time of the year for every hour in the 24.

The curves are almost exactly alike from day to day at this time of the year. It will be noticed that from 12 hours to 21 hours, that is, from noon to 9 p.m., the signal strength is about 6 or 8 $\mu$V/m. These times correspond to a period when it is daylight the whole way across the Atlantic, and when the actual transmission is the poorest. It is a time when the field intensity is lowest. What signal we get depends, of course, upon the noise. At about 9 p.m. the signal strength begins to increase. It rises from 8 to about 80 units; that is, it increases about 10 times. It continues to increase until at 2 o'clock in the morning it is up to 150 $\mu$V/m, i.e. 19 or 25 times what it was in the afternoon. That is a perfectly normal sort of thing with radio transmission, and it has an extremely important bearing upon the design of radio transmission systems, as I shall explain later. During the time in which the field is a maximum, it is night all the way across the ocean. We then begin to get daybreak here on the east side of the circuit, and, since daylight transmission is poorer than night transmission, the electric field begins to come down and finally at noon it is back to about where it was at noon the previous day.

It will be noticed that the difference is from something like 6 $\mu$V/m up to about 150—a variation of as much as 25 to 1 in the electric field.

At the same time, we have measured and plotted the noise tending to obscure this transmission. If we had no noise we should not care if we got only 0·1 $\mu$V/m, because nowadays we can amplify almost without limit. We do get noise, however, so we have to have bigger signals. The noise at noon on this particular day—and this is rather typical—was about 0·2 $\mu$V/m, as compared with 8 for a signal; in other words, a ratio of 40 to 1 of signal to noise, which allows perfectly good speech in spite of the fact that our signal is not strong. As the afternoon goes on, the noise increases until finally, at 5 p.m., we have 1 $\mu$V/m of noise and only 8 $\mu$V/m of signal. This means that the result will be unsatisfactory; it is equivalent to a very poor telephone circuit.

The noise remains at this value all through the night, but the signal strength goes up, so that later we get very good conversation. The signal strength decreases again towards 6 o'clock in the morning. If a curve showing the ratio of signal strength to noise were plotted, it would indicate that we could get reasonably intelligible talk for 12 to 14 hours a day at this time of the year, using 60 kW at New York. For the remaining 10 or 12 hours a day we should not get satisfactory talk, and at certain times, especially about 6 o'clock at night, we should get practically no talk at all.

There is a formula which gives the signal strength at a given distance and a given frequency, due to a given current in a transmitting antenna of given effective height. That formula contains two terms, the first a term which gives us the spreading-out effect, the ordinary inverse-power law of spreading, and the second, multiplying the first, which gives us what is known as absorption due to ionization of the atmosphere, or something of that kind. The absorption factor for transatlantic communication at 60 000 periods (about what we are using) is 30 to 1. The difference between day and night transmission is represented by a clearing up of this absorption; that is, the normal field is obtained in the daytime according to this formula, and then, if the absorption is lifted, the signal increases by an amount equal to the absorption factor. For example, this signal ought to increase by 30 times between day and night if that formula were absolutely accurate, and as a matter of fact it does so. This is for long waves—5 000 to 6 000 m.

Fig. 15 shows some curves which were obtained in connection with our ship-to-shore telephone work, the work of connecting the Bell telephone system in the United States with ships, so that from the ship one can carry on a conversation with anyone in the United States. This is done on a short wave-length, viz. about 400 m, because we want to work over only 200 or 300 miles. There was such a telephone set on the s.s. "America," and this is a record of the field strength obtained, as measured in New York as the "America" came from France to New York. The ship is going towards the left-hand side of the figure. Two curves are plotted. Curve A represents the so-called Austin formula, referred to previously, which should give the daily over-water values of received field. Curve B is the same formula without the absorption factor and theoretically perhaps that is too strong, but it is plausible at least—the difference between day and night transmission ought to be equal to the difference between those curves.

When the ship is very close, only about 100 miles or so away, the observed values (marked by circles) coincide with both curves as they should do, as it is daylight. During the last night before arrival there is very little change. During the second day before arrival it will be noticed that the observed values fall almost exactly along the theoretical curve. Then on the second night before arrival we begin to get some absorption effects. There are freak effects; for instance, the field suddenly rises from 10 $\mu$V/m to 70 and then varies irregularly, finally going up, near the beginning of the second night, to 100 $\mu$V/m, as compared with a normal daylight measurement of about 6. On the third day before arrival the ship is about 900 miles away. There are not many observed points plotted, but as a matter of fact we obtained them in other curves. They fall almost exactly on this curve of the Austin formula until it is night, when we begin to get tremendous variations due to the lifting of the absorption. In other words, we get a variation of from 1 $\mu$V/m to 200 $\mu$V/m the third night before arrival, when the ship is 1 100 miles away. This is all over water. There is a ratio of 200 to 1 in the day and night values. One other point worthy of mention is not shown by these curves. These remarkably high values occur almost periodically; that is to say, there is likely to be 200 $\mu$V/m for 10 seconds and then 1 $\mu$V/m for 10 seconds, so that it is quite impossible to control the amplification of the circuit.

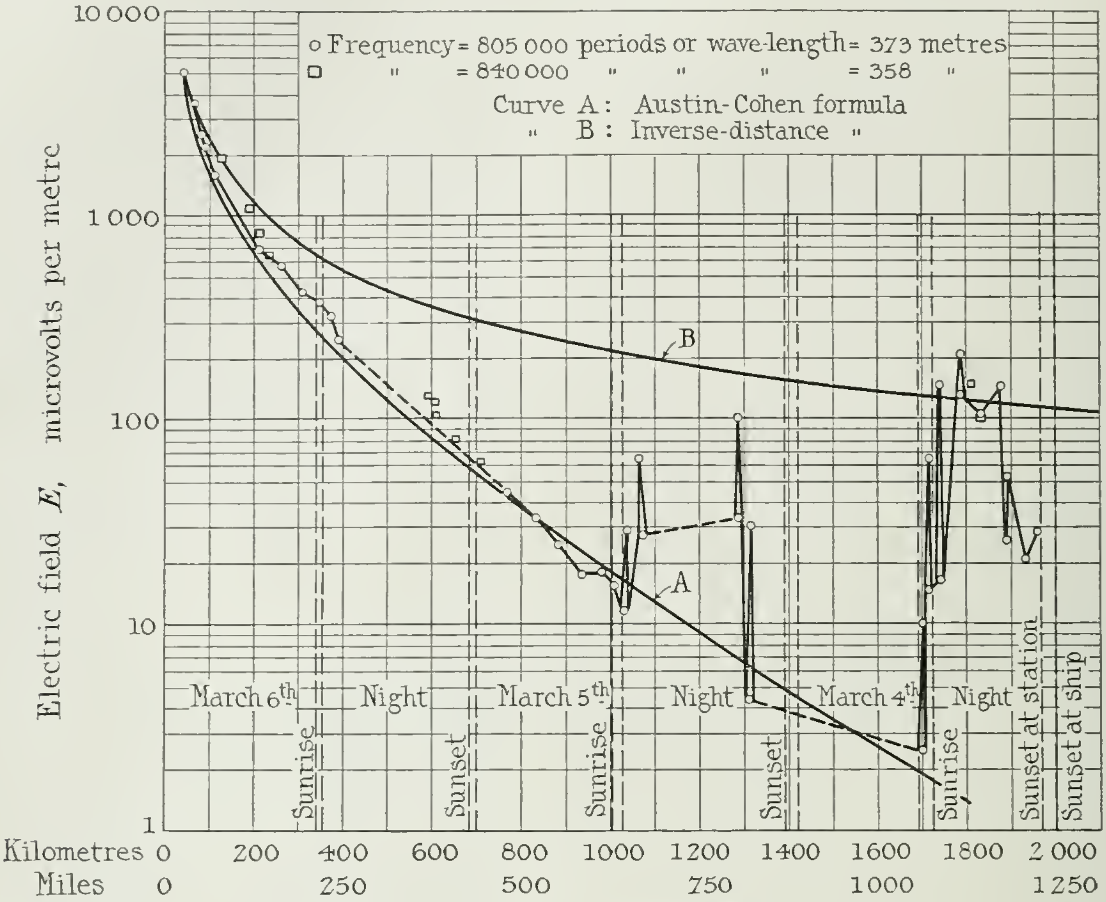


FIG. 15.—Electric field from s.s. "America," March 1922.

We have plotted a number of these curves, and this is typical of short-wave transmission as compared with long-wave transmission. The conditions are unusually favourable because all the transmission is over water.

The values will be very different during summer. In summer the noise goes up tremendously and the transmission goes down somewhat, so that in order to determine how much power will be required it will be necessary to take these measurements over a complete cycle, i.e. one year. We expect, therefore, to continue these observations until next September. The worst period is July and August; once we are through the worst period, conditions will begin to repeat themselves again. We shall therefore carry the results from July to September inclusive, so that we can determine how much power will be required at New York to maintain a commercial circuit. Whether or not such a circuit will be built depends on other than engineering considerations. We hope to have, next year, information which will allow us to design intelligently a commercial radio-telephone circuit when and if it is demanded.

## Discussion before The Institution, 22 February, 1923.

**Mr. L. B. Turner**: I should be glad if the author could give some idea of how the strengths of field were measured, the strength of signal, and especially the "noise level" shown in Fig. 14.

**Dr. W. H. Eccles**: This lecture is really the story of a long endeavour, dating back, I think, to 1913, and continued very strenuously by the best scientific methods and by great practical skill, chiefly at the hands of the author, during all these years. In 1919 and 1920 he perfected a scheme for speaking from ship to shore, and vice versa, which was tried out on the New Jersey coast, and which enabled anyone on the Bell system in America to communicate with a ship at sea within, say, 300 miles of the coast—to speak to the ship as if it were connected by land wires. I am of opinion that one reason why the system has not come into greater favour for communication between ship and shore is that other vessels when transmitting spark signals cause much interference. In the case of transoceanic telephony that kind of interference can be more easily cut out, because a different range of wave-lengths is used. Those early experiments, however, have led the author to his present success and have given him and his collaborators the great skill which has been necessary in order to carry things to their present stage. To me the most interesting and novel part of the lecture is that which deals with the propagation of waves across the ocean. The author's curves for day and night transmission, for instance, are of profound importance to all who have to design stations and circuits when great distances are to be covered. The noise curves shown on the lantern slides are presumably stray noises of a wireless origin; they are perhaps natural electrical waves, commonly called "atmospherics." I presume they are not of local origin at this time of the year, because in England in winter there are few thunderstorms and electrical discharges. I imagine, therefore, that these noises are due to natural electric waves originating in distant parts of the earth. The fact that the noise is a maximum here in England at about 5 p.m. is significant. At that moment the sun will be somewhere over Quito, and in a favourable position for causing huge electrical displays on the mountains of the Andes, and it certainly seems to be at some such point of the globe that these noises originate at that time of day.

**Mr. E. H. Shaughnessy**: The point which most impressed me in the lecture was that relating to the development of sending only the half band of frequencies, and by that means effecting such an economy in power. The author does not indulge in any large prophecies, but is prepared to push this investigation to see what is actually required in order to get transmission from America to this country. I suggest that measurements similar to those which he has taken in this country should be made in America, to make sure that a wireless telephone route in the reverse direction is feasible, because speech in one direction only is of no use. It is believed that the atmospheric conditions in America are very much worse than they are in this country, so that deductions as to the amount of power required and the capital cost for transmission from America to this country may be misleading when the question of messages from this country to America is considered.

**Mr. H. E. Morrish**: In both-way transmission, does the author mean us to understand that we should have to accept each of the eight branches which he mentioned as being available for radio-telephony as being applicable in one direction only, i.e. that we should transmit at one frequency from America to England and at another from England to America? If that is so, is there a possibility that reception and transmission could take place on the same aerial at these frequencies, or would it be necessary to have two distinct stations to transmit and receive? What distance apart would those stations have to be in the case of transmission between England and America? The limit of range of selectivity being what it is, is there any hope that directional wireless will increase the possibilities of extra circuits? If we transmit from America to England it appears to me that, under present conditions, transmission from New York to Japan, for example, would thereby be prejudiced. Has the author ever considered the possibility of forming radio screens with the idea of absorbing the current travelling in a direction in which we do not desire it to go?

**Dr. H. W. Nichols** (*in reply*): I shall deal in the first place with the measurement of noise. We are, of course, primarily a telephone company, and we have been studying speech and the quality of speech for a great many years. There has developed in our laboratory a technique for determining intelligibility and for determining the effect of noise upon intelligibility. The method we use is to introduce into the loop a siren note running up and down the whole frequency scale used in speech, all on a constant voltage, and to compare that voltage with the noise; that is to say, to determine how low that siren note can be in order that it shall be just distinguishable above the noise. That will probably seem to be rather a rough method, but it has at the back of it a great deal of information as to the effect of noise upon telephonic quality, secured in the laboratories at New York. A considerable amount of very accurate work has been done there, with the result that the data which we have now can be translated into actual intelligibility numbers.

Dr. Eccles did not ask any very definite questions. I quite agree with what he said about the noises. We get a little London noise out there, which is due to ordinary local disturbances, but I think that the general indications, particularly from the shape of the noise curve, are that we get noises from places like Turkey and further East. From the curves one can almost follow the path of the sun.

Mr. Shaughnessy is quite right about local receiving conditions in the neighbourhood of New York; they are very much worse than they are here. They are very much better in the neighbourhood of Maine than they are in New York, although probably worse than they are in England. It is certainly necessary to carry on two-way transmission, and tests in both directions will certainly have to be carried out.

Mr. Morrish asked whether or not two-way operation can be carried out on one wave-length or one band of frequencies. I should say not on one band of frequencies. In the second place, he inquired whether one antenna would be used for both transmission and reception. I am sure that would not be the case, because it is so simple to do it the other way. A loop receiving set, or a combination of loop and something else, to give a more sharply directional reception a few miles away from the transmitting set, would be all that was necessary. His last question concerned directional transmission. The answer to this is that radio waves are radiations, just as light is, and it is well known that to concentrate a beam of radiation of any kind it is necessary to employ structures having dimensions at least comparable with those of the wave-length involved, and preferably some low multiple of the wave-length. Transatlantic wave-lengths are in the order of 8 000 m, or 4 or 5 miles, so that structures in the order of 10 miles in physical dimensions would probably be required for directional transmission, and for sharp directional transmission I think that very much larger structures would be necessary. Technically it is quite possible to do it, but financially I think that there are many reasons against it.

---

# AN ELECTRODE APPARATUS FOR THE LOCATION OF SUBMARINE CABLES AND FAULTS.[*][†]

By F. B. Young, B.A., D.Sc., F.Inst.P., and W. Jevons, M.Sc., A.R.C.S.

(*Paper received 21st December, 1922.*)

## Summary.

A method is described of locating cable faults by means of a pair of towed electrodes, the cable section between fault and shore being energized by alternating or interrupted current. The limitations and difficulties of the method are discussed and remedies are indicated.

Two practical trials of the gear are briefly described.

Simple approximate formulæ are derived for the range of the gear, and numerical values are calculated for three typical cables. It is shown that the device should be sufficiently sensitive to locate an earthed break in a modern cable up to 360 nauts from shore and an insulated break up to 100 nauts, though on account of the difficulty of handling the gear in deep water the useful ranges would often be much less.

## Introduction.

When a break or fault occurs in a submarine telegraph cable it is the practice to locate the damaged point by means of electrical tests conducted at the shore ends. The cable repair ship is then navigated to the point indicated upon the chart, and drives with grapnels are made across the site of the cable until the latter is hooked. Although great skill has been developed both in making the preliminary tests and in carrying out the subsequent sea operations, the method is subject to various possibilities of error. The electrical indications are occasionally uncertain or misleading; owing to weather conditions either the cable may have been originally wrongly charted or the cable ship may make errors of navigation in working out to the break; while in congested areas the grapnel may pick up a working cable instead of the one which is damaged.

Successful trials have been carried out with a device whereby the vessel may detect the cable at a convenient distance from the shore and follow it out to the break, the delays due to inaccuracies in the tests or to navigational errors being thus avoided.

## I. General Description.

Tha apparatus consists of two metallic electrodes, D and N (Fig. 1), which are towed at the ends of two insulated conductors, of unequal length and twinned throughout their common length, by means of which they are connected through a suitable transformer, T, to a three-valve amplifier. The electrodes may conveniently consist of lengths of copper or phosphor-bronze braiding threaded over the end of the cable and soldered to the conductor. This should be protected by a covering of some stout, porous material

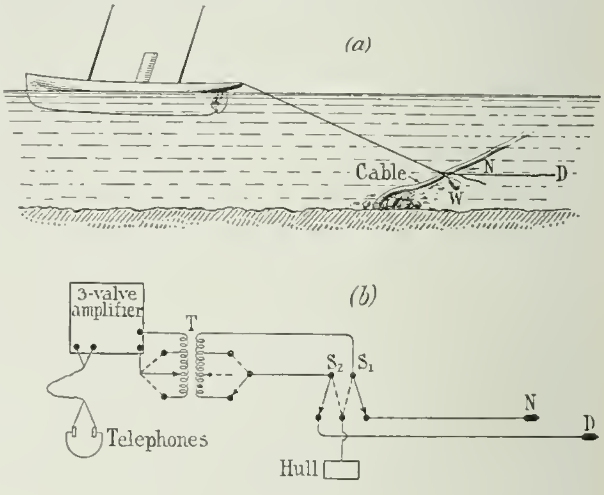


Fig. 1.

---

[*] The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] The application of the electrode gear to cable repair work was suggested by Mr. B. S. Smith.

such as hessian or a hemp pile, since friction between the metal and the sea-bottom produces serious electrical disturbances. For maximum sensitivity the towing cable should be loaded with a weight, W, so that the electrodes are towed near the ground (but see Section VI).

If an alternating current of audible frequency is passed through the cable, the oscillating magnetic field and eddy currents produced around the latter may be detected by means of the electrode circuit. Hence, by towing the electrodes obliquely across the track of the cable and changing course each time the sound heard rises to a maximum, the ship may tack along the cable until the total failure of the signals indicates that the break has been passed.

In arranging the power supply for the cable, care must be taken that the potential difference between core and sheath at no time rises above 50 volts, this being the limit prescribed by the cable companies. Thus for a sinusoidal current the maximum potential difference is $50 \div \sqrt{2}$ volts (R.M.S.) or 35 volts. A convenient source of power is a 50-volt accumulator the current from which is rapidly interrupted and reversed by means of a motor-driven commutating interrupter giving about 500 periods per second (p.p.s.). It is advisable to break up the alternating current into the dots and dashes of a Morse letter, this being readily effected by means of a low-speed rotary interrupter driven by the motor through worm reduction gear. Such Morse signals are less liable than a continuous note to be masked by disturbances due to such causes as the ship's electrical machinery.

The towing cables and deck leads must be carefully twinned in order to eliminate as far as possible electromagnetic disturbances which are almost invariably produced by the ship's machinery, whether electrical or steam-driven. These disturbances may, however, be conveniently utilized for testing the condition of the electrode circuit from time to time. By means of the testing switches $S_1$, $S_2$ either electrode may be replaced at will by the ship's steel hull, which then forms, together with the remaining electrode and its lead, an inductive circuit whereby the ship's disturbances are picked up. Failure to hear the ship's noises would indicate a break in the circuit. If preferred, a more standardized electromagnetic testing field may be obtained from a small electrical buzzer placed near the deck leads.

The sensitivity of the detector depends upon the distance between the electrodes, increasing up to a certain limit as that distance is made greater. There is little advantage, if any, in increasing the length DN beyond 40 or 50 yards. The sharpness of the maximum is increased as the length is diminished, and in practice a "base-line" DN of 10 yards has generally been employed. Any numerical data given in the paper may be assumed to refer to a pair of electrodes towed close to the sea bottom at a distance of 10 yards apart along a course inclined to the telegraph cable at an angle of 45°.

It will be observed that the electrode cable-detector bears a general resemblance to the "leader gear" now being developed for purposes of navigation, the essential difference being that towed, weighted electrodes are substituted for coils fixed on the ship's hull. It is quite possible to utilize the leader-gear coils for the detection of cable faults, but the electrodes, on account of their comparative independence of the depth, give a much more extended range;* in view of the very limited currents which are permissible this consideration proves to be of great practical importance [see Section VI, (2), (ii)].

The leader-gear coils possess, within their limited range, the advantage of giving port-starboard indications which enable the vessel to follow a more direct course. Similar indications may be obtained from electrodes by towing two pairs of electrodes on the ship's quarters, as shown in Fig. 2. By connecting the amplifier alternately to the respective pairs it is possible to determine from the relative strengths of the signals on which side of the ship the cable lies. In practical trials, however, only a single pair of electrodes has hitherto been employed.

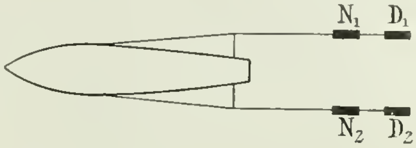


FIG. 2.

## II. RANGE OF DETECTOR.

The distance from shore at which a break may be detected is limited primarily by the attenuation suffered by an alternating current flowing through a submarine cable, due mainly to the capacity current between the core and the sheath. The attenuation constant depends upon the resistance, capacity and inductance per unit length of the cable and upon the frequency of the current. Other factors upon which the range depends are the weight of the iron wire sheathing (which acts as a screen reducing the external field due to the current) and, of course, the sensitivity of the listening apparatus, in which may be included the human ear. Finally the nature of the cable fault itself must be considered.

The selection of the frequency to be employed involves a compromise, for whilst the ear is most sensitive to frequencies of 1 000 p.p.s or higher (and it is to such frequencies that commercial telephones and amplifiers are designed most readily to respond), the attenuation of the current diminishes as the frequency is reduced. The trials and calculations that were made led to the conclusion that a frequency of about 500 p.p.s. is the most suitable.†

In sensitivity tests of the gear it was found that if a pair of electrodes 10 yards apart were towed obliquely at an angle of 45° across a cable the sheathing of which had a total cross-section of 0·19 sq. in., it was possible to detect with certainty a core current of as little as 0·2 mA. As these tests were made under practical conditions, no special precautions being taken against disturbing noises due to the ship's machinery and steering gear, the result may be safely taken as a datum for range calculations.

---

* The term "range" in the paper is employed to denote the distance from shore up to which the cable may be detected.

† That is, if commercial amplifiers and telephone receivers are employed. With suitably designed apparatus the range might be extended by reducing the frequency. It is even possible that subsonic frequencies might be employed with advantage.

At the break or fault the resistance to earth of the core may vary from a very low value to infinity, according to the nature of the contact between the copper and the sea water. The fault is most readily detected when the resistance to earth is low. It is calculated (see Appendix) that an earthed fault in a typical modern cable of average resistance (about 3·1 ohms per naut) should be detectable at a distance from shore of 360 nauts, an input E.M.F. of 35 volts (R.M.S.) being assumed. This may be taken as a mean value for cables in general. The calculated ranges for two extreme cases are given in the Appendix.

If the break or fault is insulated the current passing through it is, of course, nil, but the cable can still, by means of its capacity current, be followed out to a point at which this current falls to the minimum audible strength. In such a case the point indicated by the detector will not be at the break itself but at a certain distance $d$ to shoreward. The greater the distance of the break from shore, the greater is the distance $d$, and the detector ceases to be of use when $d$ becomes excessive. In the Appendix it is shown that up to a distance of 100 nauts from shore an insulated break in the 3·1 ohm cable should be located to within 40 or 50 yards. Beyond 100 nauts the distance $d$ steadily increases to nearly 400 yards at 200 nauts, and 1·4 nauts at 300 nauts. It is obvious that insulated breaks are much less readily detected than those which are earthed, but fortunately the latter are of far more frequent occurrence.

Since no sea trials have been carried out at a greater distance from shore than about 16 miles, the above-stated ranges lack experimental verification. It is probable, however, that the useful range will generally be determined by other considerations. As the depth increases, both the length and the strength of the towing cable must be increased correspondingly, and the gear will cease to be of value when the advantages which it offers are outweighed by the delays and difficulties involved in its use. The limiting depth must be determined by experience; it can only be stated that at the depth of 50 or 60 fathoms no difficulty was experienced.

Since the majority of breaks occur near the shore and in rather shallow waters, the limitations either of range or of depth do not seriously restrict the utility of the gear.

### III. Distribution of Current in Cable. End Reflection.

Certain phenomena which have hitherto been largely of academic interest become of practical importance in connection with the apparatus under discussion.

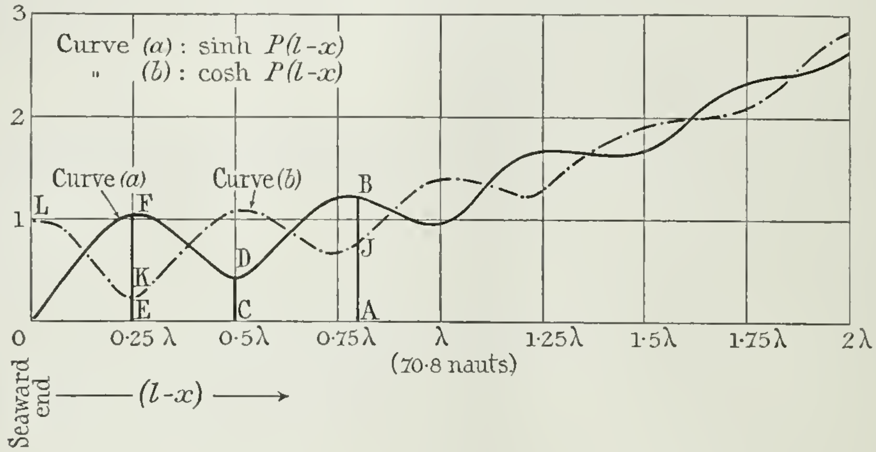


FIG. 3.

Curve ($a$) represents the relative potential distribution along cable earthed at seaward end (or current distribution along cable insulated at seaward end).

Curve ($b$) represents the relative current distribution along cable earthed at seaward end (or potential distribution along cable insulated at seaward end)

*Cable constants:* $R = 1{\cdot}7$ ohms per naut; $K = 0{\cdot}41\,\mu F$ per naut; $L =$ mH per naut; frequency = 500 p.p.s.; wave-length of propagation = 70·8 nauts.

Owing to the peculiar wave-like propagation of an alternating current in a submarine cable, reflection analogous to the reflection of sound waves at the end of an air-filled pipe occurs at the cable end, and the interference between the incident and reflected waves results in an uneven distribution of current and potential.

Curves ($a$) and ($b$) in Fig. 3 represent respectively the potential and current distribution in a cable ($R = 1{\cdot}7$ ohms per naut) the seaward end of which is earthed. In this diagram the end (or break) of the cable is represented by O. The shore (or input) end of the cable may be at points A, C, E, etc., according to the distance from station to break. That is to say, the end or break is represented by a fixed point, while the input end or station is variable in position. The scale of lengths is shown for convenience in terms of $\lambda$, the wave-length of propagation. The relative distribution of potential along a cable of any length OA is represented by the portion OB of the curve which OA subtends. In order that the curve may represent also the absolute values, the scale of ordinates must be so chosen that AB represents the input voltage. Similarly the portion LJ of curve (*b*) represents the relative current distribution, or, if AJ is taken as representing the input current, the absolute distribution.

The distribution of potential and current along a cable whose end is insulated is represented by the same pair of curves; but the potential distribution is now represented by (*b*), whilst (*a*) represents the distribution of current.

### **IV.** POTENTIAL DISTRIBUTION. DANGER OF EXCESS VOLTAGE.

From what has been said it follows that the voltage $E_0$ at the sending end may quite possibly be exceeded by the voltage at other points. If, for example, the length of the cable is $\lambda/2$, the end being earthed, then at a point $\lambda/4$ from the end the potential is $E_0 \times$ EF/CD $= E_0 \times 2{\cdot}35$. The excess voltage in a cable with end insulated may be even greater, for if the length is $\lambda/4$ then at the sealed end the potential is $E_0' \times$ OL/EK $= E_0' \times 4{\cdot}7$.

Cable experts do not seem to be quite agreed as to the necessity for the restriction of the maximum dielectric strain to 50 volts. The dielectric strength of the insulation is enormously in excess of that implied, and the regulation is presumably a refinement of precaution intended to secure a short period of additional service from a cable which is on the point of breaking down. If the restriction is to be respected, however, it is obvious that a sending E.M.F. of 35 volts cannot be used indiscriminately.

If $U'$ is the greatest possible value, for a cable of given pattern, of the ratio of the dielectric strain at the further end to that at the sending end, all danger of overstrain is avoided by invariably restricting the input E.M.F. to $35/U'$ volts. For the $1{\cdot}7$ ohm cable the permissible input E.M.F. would be 35 volts $\div\ 4{\cdot}7$, or only about $7{\cdot}5$ volts. Such a precaution is, however, unnecessarily severe.

The curves in Fig. 3 show that the conditions for a high excess voltage are also the conditions for an abnormally large input current $I_0$. If a power supply at 35 volts is employed in series with a guard resistance $r$, then the voltage-drop $rI_0$ increases or diminishes with the tendency toward excess voltage. It is shown in the Appendix that the cable is safeguarded under all conditions if $r = Z_0(1 - 1/U')$. For the $1{\cdot}7$ ohm cable this is equivalent to 50 ohms.

More efficient methods of adjusting the input voltage are possible if it is desired to employ the maximum E.M.F. which the particular condition of the cable will permit. Such methods must, however, be employed with caution owing to the possibility of sudden changes in the cable conditions. If, for example, the length of the cable is $\lambda/4$ and the end is earthed, then the excess voltage is nil and the full E.M.F. of 35 volts may be employed. Should, however, the end be grapnelled and raised whilst the current is still flowing, then, since the core is thereby insulated, the conditions for a maximum excess voltage are suddenly realized and the dielectric strain rises to $35 \times \sqrt{2} \times 4{\cdot}7$ volts $= 235$ volts. The guard resistance should produce no inconvenient reduction of the cable current unless the break is at a considerable distance from shore, in which case $r$ may be eliminated without danger.

Owing to its low resistance the $1{\cdot}7$ ohm cable represents an extreme case. As the resistance increases $U'$ diminishes. For the typical $3{\cdot}1$ ohm cable $U' = 2{\cdot}7$ and no minimum occurs beyond $\lambda/2$ from the end, whilst excess voltage does not occur in the case of a cable having the abnormally high resistance of 14 ohms per naut.

### **V.** CURRENT DISTRIBUTION. DANGER OF FALSE INDICATIONS.

From Fig. 3 it follows that the strength of the signals received by the electrode circuit may not fall off regularly along the cable. In the case of an earthed break the signals will in fact normally increase in strength as the break is approached, with the resultant advantage that the position of the latter is well defined. The uneven current distribution need cause no trouble except when the break occurs at extreme ranges, but in such cases there is a distinct possibility of false inferences. If, for instance, in the case of the $1{\cdot}7$ ohm cable the current at the break is only just detectable, then it may be deduced from curve (*b*) (Fig. 3) that on account of the minimum at $0{\cdot}75\lambda$ ($= 52$ nauts) an observer following the cable from shore would cease to receive signals at about 60 nauts from the end; the signals would come in again at about 40 nauts, to be lost once more at 30 nauts.

If it is desired to employ the detector at extreme ranges the sending apparatus should be arranged to give alternate signals of two different frequencies (e.g. 400 p.p.s. and 600 p.p.s.). The wave-length of propagation is approximately inversely proportional to the frequency; hence the maxima and minima for the two signals will occur at different points and the signals will fail simultaneously only at the end of the cable.

As remarked in Section IV, the $1{\cdot}7$ ohm cable presents an extreme case, so that the dangers of false indications are in general much less than this example would indicate.

### **VI.** SEA TRIALS OF THE ELECTRODE CABLE DETECTOR.

The following brief accounts of two practical trials of the detector will serve to give some idea of its capabilities.

(1) *Location of cable break in Ballinskelligs Bay.*—The first trial was made at the invitation of Messrs. Clark, Forde and Taylor on a cable belonging to the Commercial Cable Co. which had broken near the shore-end at Waterville, Co. Kerry. A special feature of the case was that, owing to the large number of cables converging on Waterville, to drag for any given cable was a delicate and difficult operation.

The customary electrical tests gave rather uncertain results but were judged to indicate a break at about 3 nauts from the shore end. The search with electrodes was therefore commenced at about $1\frac{1}{2}$ nauts out, but no signals were received from the cable, though several working cables were readily detected by the Morse signals passing through them, the sounds in the telephone receivers closely resembling the tapping of a Morse key. Working nearer in shore the repair ship finally picked up the a.c. signals and the indicated position of the break was buoyed. As a safeguard, previous to grapnelling the cable two neighbouring cables were also located by means of the working currents and buoyed. Owing to the congestion of cables, however, a diver was employed and the broken end was found within about 15 fathoms of the buoy and about 1·3 nauts from shore.

The actual break was thus located at 1·7 nauts from the supposed position. The significance of this lies in the fact that between the supposed and the actual position of the break the cable was crossed by three more recent cables. Hence the electrode detector undoubtedly saved considerable time and expense.

The break had occurred in the heavily-armoured shore section of "rock cable," for which the particulars were as follows: $R = 3\cdot1$ ohms per naut; $K = 0\cdot41\ \mu$F per naut; total cross-section of sheathing $= 0\cdot92$ sq. in. The input current supplied from a secondary battery through a rotary interrupting commutator giving a frequency of about 500 p.p.s. was reduced by means of resistance to 150 mA. Owing to fouling of the weight on the rocky bottom the final search was conducted with unweighted electrodes.

(2) *Location of cable break off the coast of Co. Kerry.*—This trial was carried out at the invitation of the Telegraph Construction and Maintenance Co. by arrangement with the Commercial Cable Co.

The shore tests had indicated a break at 15·7 nauts from the shore end. The electrodes were lowered at about 7 miles out and by following a zig-zag course the vessel was able readily to detect the cable at point after point until the signals ceased. The observer then stated that the break lay between the last two points crossed, and the subsequent operations showed this statement to be correct. These points were about 1 mile apart and owing to some misconception the limiting distance was not reduced, though this could doubtless have readily been done.

In this case the break proved to have been located by the shore tests to within 190 fathoms, so that no such striking demonstration of the value of the apparatus occurred as in the earlier trial. The trial, however, presented certain features of interest.

(i) The points indicated by the electrode gear lay consistently to the north of the charted position of the cable, the discrepancy at places amounting to $\frac{1}{2}$ mile. From observations already made on the occasions of two earlier repairs it had been inferred that the chart was in error. The electrode indications agreed with those observations and afforded data for the recharting of the position of the cable.

(ii) On this occasion leader-gear coils were carried, in addition to the electrodes. Owing, however, to the small input E.M.F. which was permissible and to the depth of the water, the coils failed to pick up signals beyond $4\frac{1}{4}$ miles from the shore-end (depth of water 23 fathoms; the break occurred in 50–60 fathoms). These coils have certain definite advantages over the electrodes, being more conveniently handled and permitting of following the cable practically on a straight course, but their use is apparently restricted to a very short distance from the shore.

(iii) By means of a variable shunt across the telephones a rough comparative estimate was made of the strength of signals. The signals grew markedly louder toward the end of the cable.

(iv) The cable was raised and cut at a short distance to landward of the break before the current was switched off at the shore station. At the moment when the cable was severed an observer at the station noted that the input current rose suddenly from its previous value of 0·3 ampere to 0·65 ampere.

Observations (iii) and (iv) find their explanation in the phenomena of end reflection. The cable in question had the following constants per naut, approximately; $R = 2\cdot35$ ohms, $K = 0\cdot42\ \mu$F, $L = 2$ mH (assumed). These constants imply at 500 p.p.s. a propagation wave-length of 69 nauts; hence the length of cable to the break, 15·7 nauts, was roughly a quarter wave-length and the observed phenomena exemplify the effects of end reflection discussed in Sections III to V.

It may be mentioned that, as on the earlier occasion, trouble was experienced with the weight owing to the rocky bottom, and the latter part of the operations was carried out with unweighted electrodes.

The authors desire to acknowledge their indebtedness to the Admiralty for permission to publish this paper, to the Commercial Cable Co. and the Telegraph Construction and Maintenance Co. for the facilities afforded to test the gear, and to Messrs. Clark, Forde and Taylor for their practical interest and assistance.

## APPENDIX.

### MATHEMATICAL NOTES.

If $R$, $K$ and $L$ are respectively the resistance, capacity and inductance per naut;

$l$ is the length of cable from shore to break;

$E_0$, $I_0$ are respectively the E.M.F. and current at the sending end; and

$E_x$, $I_x$ are respectively the E.M.F. and current at a distance $x$ from the sending end;

then, if the leakance of the cable is regarded as negligible,

the propagation constant $P = \alpha + j\beta$,*

the characteristic impedance $Z_0 = \sqrt{[(R + jpL)/jpK]}$

and the wave-length of propagation $\lambda = 2\pi/\beta$.

* Where the attenuation constant

$$\alpha = \sqrt{\left[\tfrac{1}{2}pK\left\{\sqrt{(R^2 + p^2L^2)} - pL\right\}\right]}$$

and the wave-length constant—

$$\beta = \sqrt{\left[\tfrac{1}{2}pK\left\{\sqrt{(R^2 + p^2L^2)} + pL\right\}\right]}$$

If the cable is earthed at the seaward end,

$$E_x = \frac{E_0 \sinh P(l-x)}{\sinh Pl} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$I_x = \frac{E_0 \cosh P(l-x)}{Z_0 \sinh Pl} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If the cable is insulated at the seaward end,

$$E'_x = \frac{E'_0 \cosh P(l-x)}{\cosh Pl} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$I'_x = \frac{E'_0 \sinh P(l-x)}{Z_0 \cosh Pl} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Inspection of Equations (1) to (4) shows that the relative distribution of potential or current is given in each case by plotting the function $P(l-x)$ in the numerator against $(l-x)$, the distance from the seaward end of the cable (see Fig. 3).

TABLE GIVING PRACTICAL DATA FOR THREE TYPICAL CABLES.

*Frequency* 500 *p.p.s.*

The cable sheathing is assumed to have a cross-section of 0·35 sq. in. (equivalent to 12 wires of No. 6 S.W.G.). The ranges are calculated on the assumption that $E_0 = 35$ volts (R.M.S.).

| Cable | Cable constants, per naut | | | Attenuation constant, $a$ | Wave-length constant, $\beta$ | Characteristic impedance, $Z_0$ | $\lambda \left(= \frac{2\pi}{\beta}\right)$ | $D$ (extreme range when cable end is earthed) | $U''$ (maximum excess voltage) | $r$ (guard resistance) |
|---|---|---|---|---|---|---|---|---|---|---|
| | $R$ | $K$ | $L$ | | | | | | | |
| | ohms | μF | mH | | | | | nauts | volts | ohms |
| A | 1·7 | 0·41 | (2)* | 0·012 | 0·089 | 71 | 71 | 650 | 4·7 | 56 |
| B | 3·1 | 0·41 | (2)* | 0·0217 | 0·094 | 74 | 67 | 360 | 2·7 | 47 |
| C | 14 | 0·32 | (2)* | 0·068 | 0·104 | 123 | 60 | 110 | (0·84)† | 0 |

Note.—A represents a cable of extremely low resistance. B represents a modern cable of medium resistance. C represents a cable of extremely high resistance and is now almost obsolete. It occurs at sea in a few original sections of early cables only.

* Value of inductance assumed (see above). † The fractional value for $U''$ implies that excess voltage does not occur.

In the following deductions from Equations (1) to (4) the magnitudes only of the results are given, the vectorial angles being disregarded.

### RANGE OF DETECTION.

(*a*) *End earthed.*—From Equation (2),

$$I_l = E_0/(Z_0 \sinh Pl)$$

If $l$ is so great that $\cosh al = \sinh al$ (approximately), then $I_l = (E_0/Z_0) \times 2\epsilon^{-al}$ (approximately).

If $i$ is the minimum cable current detectable by the electrode gear, and $D$ the maximum distance from shore at which the break can be detected,

$$I_l = \frac{E_0}{Z_0} \times 2\epsilon^{-aD} = i$$

whence $$D = -\frac{2{\cdot}30}{a} \log \frac{iZ_0}{2E_0} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The value of $i$ depends upon the thickness of the cable sheathing. From experiment (see Section 11), for a cable having a sheathing of total cross-section 0·19 sq. in., $i = 0{\cdot}2$ mA. The allowance to be made for variations in the thickness of the sheathing is rather uncertain, and probably involves consideration of the structure as well as of the weight. From Oldenburg's calculations,* however, it is inferred that within practical limits, if the area of cross-section of the cable is $S$ sq. in.,

$$i = 2 \times 10^{-4} \times S/0{\cdot}19 \text{ (approximately)} \quad . \quad (6)$$

In the table are given the values of $D$ calculated from Equations (5) and (6) for three cables A, B and C of extremely low, medium and extremely high resistance respectively. The constants $R$ and $K$ were supplied by cable companies. The values of $L$ were unobtainable, and in the absence of any opportunity for satisfactory tests a value of 2mH per naut has been assumed. This is near the lower limit specified by Malcolm † and is in fair agreement with experimental values obtained by Pernot.‡

Since Equation (6) involves a rather doubtful assumption, it may be pointed out that if the factor of error in $i$ is $2^n$, then, from (5), the error in $D$ is $-(2{\cdot}30\, n/a) \log 2$. For cable B this is equivalent to 30 nauts × $n$; thus if $i$ should be given twice the correct value, the value of $D$ is affected by less than 10 per cent.

(*b*) *End insulated.*—From Equation (4), provided $(l-x)$ is small compared with $\lambda$,

$$I'_x = \frac{E'_0 pK(l-x)}{\cosh Pl} \text{ (approximately)}$$

whence, if $d$ is the value of $(l-x)$ for which $I'_x = i$,

$$d = \frac{i \cosh Pl}{E'_0 pK}$$

---

* *Archiv für Elektrotechnik*, 1920, vol. 9, p. 289.

† "Theory of the Submarine Cable," p. 34.

‡ *Journal of the Franklin Institute*, 1920, vol. 190, p. 323.

In the case of cable B

if $l =$ 33 nauts, $d =$ 0·005 naut or about 10 yards
,, 100 nauts, ,, 0·0183 naut or about 37 yards
,, 200 nauts, ,, 0·159 naut or about 320 yards
,, 300 nauts, ,, 1·39 nauts

Hence in the case of a modern cable of average resistance the electrode detector should be capable of locating an insulated break up to a range of at least 100 nauts to within 40 or 50 yards.

### EXCESS VOLTAGE DUE TO END REFLECTION.

If "excess voltage" is defined as the ratio of the maximum E.M.F. in the cable to the E.M.F. at the sending end, and if $U$ is the maximum possible excess voltage for a cable of given type assumed to be earthed at the seaward end, then from curve ($a$) (Fig. 3) and Equation (1),

$$U = \frac{\sinh P(\lambda/2 - \lambda/4)}{\sinh P(\lambda/2)} = \tfrac{1}{2}\operatorname{cosech}\frac{\alpha\pi}{2\beta} \quad . \quad . \quad (7)$$

Similarly for the insulated cable [writing $l = x = \lambda/4$ in Equation (3)]

$$U' = \frac{\cosh P(0)}{\cosh P(\lambda/4)} = \operatorname{cosech}\frac{\alpha\pi}{2\beta} \quad . \quad . \quad . \quad (8)$$

From (7) and (8) it follows that the insulated cable is liable to an excess voltage twice as great as that to which the earthed cable may be subjected.

The values of $U'$ are given in the table for cables A, B and C. In cable C at frequency 500 p.p.s. the phenomenon of excess voltage does not occur and Equation (8) ceases to be applicable.

If cosech $(\alpha/\beta)(\pi/2)$ is plotted against frequency it will be found to diminish regularly as the frequency is diminished. The danger of excess voltage can therefore be diminished by working at a lower frequency. To obviate the effect entirely in the case of cable A would, however, involve the reduction of the frequency below 100 p.p.s.

### GUARD RESISTANCE.

In the case of a cable of length $\lambda/4$ insulated at the end, the sending-end impedance

$$\frac{E'_0}{I'_0} = \frac{Z_0}{\tanh P(\lambda/4)} = \frac{Z_0 \sinh(\alpha/\beta)(\pi/2)}{\cosh(\alpha/\beta)(\pi/2)} = Z'$$

It is required in the case in question that $E_0$ should not be greater than $E/U' = E \sinh(\alpha/\beta)(\pi/2)$, where $E$ is the maximum E.M.F. to which the cable dielectric may be subjected. If $E$ is also the E.M.F. of the power supply, the condition will be fulfilled if a guard resistance $r$ is used in series with the power supply and cable such that

$$\frac{Z'}{Z' + r} = \frac{1}{U'}$$

i.e. such that

$$r = Z_0\left(1 - \frac{1}{U'}\right)\frac{1}{\cosh(\alpha/\beta)(\pi/2)}$$

Since $\cosh(\alpha/\beta)(\pi/2)$ is always rather greater than 1, the cable is fully protected by making $r = Z_0(1 - 1/U')$.

# THE DRIVE OF POWER STATION AUXILIARIES.

By L. Breach, Member, and H. Midgley, B.Sc. (Eng.), Associate Member.

(*Paper first received* 29*th November*, 1922, *and in final form* 16*th February*, 1923; *read before* The Institution 26*th April, before the* Mersey and North Wales (Liverpool) Centre 16*th April, and before the* Scottish Centre 27*th April*, 1923.)

### Summary.

The paper deals only with the supply of power for the auxiliaries of a modern power station, no attempt being made to discuss the relative merits of apparatus such as evaporators, ejectors, etc.

The following aspects of the problem are dealt with:—

(1) Consideration of the different types of auxiliaries used in a station.
(2) Consideration of the different types of supplies available.
(3) Suitability of different auxiliaries and supplies for various conditions of station working.

Seven alternative schemes for the supply to the auxiliaries of a proposed new station are described and tabulated, and the advantages and disadvantages of each are considered in turn.

Certain of these are recommended by the authors, this recommendation being based on the principle that no expense should be spared to secure a simple and reliable system of station auxiliaries.

Some observations are made on features to be taken care of when auxiliary supplies are being laid down.

### Introduction.

The general question of the drive of power station auxiliaries is one which is receiving an increasing amount of attention from up-to-date power station operating and designing engineers.

In the case of the early generating plants, consisting of Lancashire boilers with natural draught and hand stoking, supplying steam to simple condensing reciprocating engines, with condenser pumps coupled mechanically to the main engines, practically the only auxiliaries requiring a separate drive were the feed pumps, which were usually of the steam-driven reciprocating type.

At the present time, however, auxiliaries of power plants require a very large amount of thought and attention from the designing engineer, and it is therefore proposed to consider in the paper a few of the points to be watched when the arrangements for a new power station are being prepared.

When preparing a scheme for the auxiliaries, one of the first questions which arises is as to the purpose of the station, i.e. whether it is for constant running on a high load factor, possibly taking a "base load," whether it is for an ordinary commercial load of an annual load factor of about 30 per cent, or whether it may only have to run for a few hours in the year, as in the case of a station which acts as a stand-by to a hydro-electric supply. In other words, it is essential to know whether continuity of supply or simplicity of design is the more important factor, for it is obvious that an expenditure on auxiliaries which would be justified in the case of a central supply station feeding an important industrial area would be extravagant in the case of a stand-by station to be used only at infrequent intervals.

It should therefore be noted that only a modern station equipped with large turbo-alternators, mechanical stoking, etc., is dealt with in this paper, and attention has been confined to the supply of power for the auxiliaries, i.e. no attempt has been made to include the discussion of the merits and demerits of such apparatus as evaporators, ejectors, etc.

It is, of course, obvious that it is very difficult to lay down any general rules as to which is the best system of auxiliary supply, for there are many cases where alternative schemes are technically equal, and the choice may quite well be based on the likes and dislikes of the engineer who will be responsible for the running of the station. It is proposed, therefore, to deal with three main aspects of the problem and to outline the more important features of these aspects, which are as follows:—

(1) The consideration of the different types of auxiliaries which may be used in a station, and their individual requirements and relative importance.
(2) The consideration of the different types of supplies available for the auxiliaries.
(3) The consideration of the suitability of different combinations of auxiliaries and supplies under different conditions of station working.

### (1) The Different Types of Auxiliaries.

For the purpose of considering alternative systems of drive, the auxiliaries in a power station may best be grouped according to the length of time during which they may be shut down without causing serious inconvenience and even damage, and this time depends upon:—

The importance of keeping the station on load without intermission, and
The importance of keeping the individual turbo-alternators on load without intermission.

It may be taken as an axiom that in a large power station with turbo-alternators each of not less than 10 000 kW capacity, loss of vacuum must at all costs be avoided, not only because of the fact that the output falls by about 60 per cent when the turbine exhausts to atmosphere, but more important still, because the rise of temperature of the blades at the low-pressure end, consequent upon the heat from the windage losses, may cause serious distortion and damage.

We may therefore divide the auxiliaries into four types:

(*a*) Those which must not on any account stop. This includes the main circulating water supply, the air extraction, and station lighting.
(*b*) Those which must not stop for more than, say, 60 seconds. This includes the boiler feed-pump, and the power for the control circuits.
(*c*) Those which may stop for up to about five minutes, but not longer. This includes water extraction, individual stokers, individual forced-draught and induced-draught fans, and ventilating fans.
(*d*) Those which may stop for a period of up to about 12 hours without shutting down the station. This includes coal and ash conveyers, coal crushers, pumps for water-softening plants, and economizer-scraper motors.

*Type* (*a*).—Unless the flow of circulating water through the condenser tubes is due, in whole or in part, to gravity (a highly desirable state of affairs which can rarely be obtained except in hilly countries), it is evident that a stoppage of the circulating water pump will mean a stoppage of the flow of circulating water. As the full-load input of steam would boil the water contained in the tubes in about 50 seconds (the exact time depending on the design of the condenser) a stoppage of the circulating pump consequently means an immediate loss of vacuum. That a loss of vacuum will at once follow a stoppage of the air extraction is a self-evident fact.

The only way to ensure continuity of supply for these duties is to have pumps in duplicate, each of sufficient size to carry the load without too great a loss of vacuum, and drive each pump of the pair from a totally different supply. It is, of course, possible that both supplies might fail at the same time, but, if the sources of supply are kept absolutely independent, the chances of this are so slight that for all practical purposes such duplication may be considered to give continuity of supply. For example, one pump steam-driven and the other driven by a motor supplied from the main busbars would satisfy the requirements, but one pump driven by an a.c. motor fed from the main busbars through a transformer, and the other pump driven by a d.c. motor obtaining its supply from a rotary converter supplied through a transformer also from the same section of the main busbars, would not be a good example of duplication, as a fault on that section of the main busbars might shut down both the a.c. and d.c. supplies. This point will be dealt with in more detail later in the paper.

The importance of having alternative supplies for the station lighting is obvious, as should this fail at the moment when a fault occurs on the main supply, the demoralizing effect that always follows total darkness would greatly accentuate the inconvenience due to the fault

*Type* (*b*).—The classification of the boiler feed-pump under this section is consequent upon the high rates of evaporation now obtained in water-tube boilers, in which the water-level will fall to a dangerous degree if the feed supply fails for more than about a minute when the boilers are on full load.

This group of auxiliaries must be so arranged that, in the event of a failure of supply, another is immediately available. For the boiler feed-pumps one of the most suitable schemes is to have one motor-driven rotary pump and one steam-driven rotary pump for each group of boilers, either pump alone being capable of feeding the group, the pump which is not on load being always kept ready for immediate use.

*Type* (*c*).—For the auxiliaries of this class an alternative supply must be readily available, but it need not be immediately available, a suitable arrangement being to have this type of auxiliaries so arranged that they may all be fed from either of two alternative supplies, the change-over being effected, when required, by means of selector switches, the motors being first shut down and then started up again on the new supply.

It will have been noted that under Type (*c*) were included individual stokers and individual fans. The stoppage of one or two stokers or fans even at a period of peak load, whilst being inconvenient, would not be necessarily serious, but it is well realized that for all the stokers or all the fans to break down at such a time would be disastrous, and therefore the whole group of stokers or the whole group of fans would come under Type (*b*). As will be seen later, this point has been taken into account in the schemes put forward.

*Type* (*d*).—In this case the usual practice is to carry spares for such parts as are likely to cause trouble, e.g. motor armatures and field coils. These can be installed without entailing a shut-down of more than a few hours, during which time the auxiliary can be dispensed with. It will be obvious that in the case of coal-conveyor motors, for instance, it should be possible to rely on the supply in the service bunkers for such time as is required to replace the armature of the motor.

To some degree the relative importance of the various auxiliaries depends upon the conditions under which the station is operating, but this feature will be dealt with when the various schemes are considered.

### (2) Consideration of the Different Types of Auxiliary Supply available.

There are many types of auxiliary supply, the following being the more important:—

(A) Direct steam drive.
(B) Electric, from main alternators via high-tension busbars.
(C) Electric, from main alternators direct.
(D) Electric, from main alternators via special windings on main transformers.
(E) Electric, from special steam-driven a.c. or d.c. generator (house set).
(F) Electric, from special a.c. or d.c. generator on shaft of main turbo-alternator.

Each alternative supply must be examined as to its suitability under the following circumstances:—

(*a*) Starting up, for the first set on a system and also for subsequent sets.
(*b*) Running on full load and also on no load.
(*c*) Shutting down any section of the system.
(*d*) All conditions of faults on the electrical end of the station and of the system.

Also all the alternative arrangements must be considered from the following points of view, in the order given.

(i) Reliability.
(ii) Simplicity or foolproofness.
(iii) Attention required.
(iv) First cost.
(v) Effect on overall efficiency of station.
(vi) Complete working costs, including charges on capital cost.
(vii) Effect on feed temperature or "heat balance."

In the authors' opinion, the question of cost should be considered only when maximum reliability has been assured, and, in the case of a public supply, if there is any difference in reliability between two alternatives the costs should not affect the decision.

After all, the cost of the auxiliary plant is only about 5 per cent of the total cost of a new station, and it would appear to be false economy to jeopardize continuity of supply through any saving which might be made in the first cost of such plant.

A few of the more important features of these alternative supplies may with advantage be noted.

(A) *Direct steam drive.*—This may be by either turbine or engine. On the whole, direct steam drive requires more attention than electric drive, but it has the advantage of being absolutely independent of any disturbances on the electrical system. For any except very small sizes the engine type need not be considered, but the turbine either direct-coupled or geared fills a very useful place.

Of course, at times of heavy load, if the main steam pressure falls the power and speed of direct steam-driven auxiliaries will fall just when they may be most needed; this is especially the case where an auxiliary turbine driving a main circulating pump exhausts into one of the main turbines near the low-pressure end, for under the heavy-load condition the back pressure in the main set rises, with a consequent increase in steam consumption and fall of speed of the auxiliary turbine. This causes a further fall of vacuum of the main set, and so the vicious circle goes on, with the result that the frequency of supply may be reduced until the load eases down.

A considerable amount of attention is required to keep tight the many steam-pipe joints entailed with direct steam auxiliaries, and the overall thermal efficiency of the station is reduced by the heat losses due to increased radiation surfaces, etc. Further (and now that the importance of really pure de-aerated feed water is being more and more realized, this is a matter of considerable weight), the use of direct steam drive increases the make-up to almost double, the experience of one American supply company being that the adoption of electrically driven auxiliaries reduced the make-up of the total boiler feed in circulation from 6 per cent to 3 per cent.

The one auxiliary for which direct steam drive is especially suitable is the boiler feed-pump, the exhaust steam being utilized to heat the feed water, this being particularly convenient when, for any reason, the main feed-heating arrangements are out of action.

(B) *Electric drive from main alternator via H.T. busbars.*—This auxiliary supply, if alternating current, may be at the busbar voltage or reduced by means of transformers, whilst in the case of direct current the voltage may be whatever is found convenient. Now that the building of a.c. motors of above about 50 h.p. at voltages higher than 400/500 is a matter of little difficulty, the use of the main generation voltage, or at any rate a voltage of the order of 3 000, merits careful consideration.

Assuming the main generation voltage to be 6 600, this would be too high for any motors except those for the main circulating pumps. A pressure of 3 000 volts would be suitable for the main circulating-pump motors, the air-pump and extraction-pump motors (where these latter pumps are both driven by the same motor), and the boiler feed-pump motor, but there appears to be little advantage in stepping down to this pressure. In view of the extra cost of the insulation for 3 000 volts above the more usual voltage of 400, once it has been decided to step down for the auxiliaries it seems just as suitable to step right down to 400 volts for all motors rather than introduce another voltage intermediate between that and the main generation voltage.

*Alternating current versus direct current for auxiliary motors.*—This is a very much discussed question, and a few remarks on the factors effecting the choice may be of interest.

Direct-current motors require frequent attention to the commutating gear to avoid sparking, and although they are often seen running without any apparent trouble in an atmosphere full of grit and dust, nevertheless the d.c. motor requires more attention than the a.c. motor.

Direct-current motors can be economically subjected to speed regulation over a wide range and, perhaps most important of all, they can be run off a battery in times of breakdown or other emergency.

The greatest disadvantage of a.c. induction motors lies in the fact that speed regulation is not an economical proposition. Of course the speed of a slip-ring motor can be varied by varying the resistance in the rotor circuit, but this is a very wasteful method, and the system of having a controller to alter the connections of the stator windings and so alter the number of poles, is only suitable for three or four speeds at the most. Variable-speed motors working on the "cascade" principle might be used, but these give only a limited number of speeds, which are fixed by the number of poles. As final regulation must therefore be obtained by the use of valves or dampers, there is no advantage in the installation of this type of motor as compared with the ordinary asynchronous type.

On the other hand, in the case of pumps and fans, which form a very large proportion of power station auxiliaries, the output can be reduced by throttling, i.e. by control with valves or dampers.

It would be interesting to know whether in actual practice this method of control is any less efficient than the use of variable-speed d.c. motors.

Alternating-current motors, of course, require much less attention than direct-current motors, especially if, in the case of slip-ring motors, brush-lifting gear is fitted. They can run for very long periods without attention, and without having to be stopped for examination.

The fact that an a.c. motor is not suited for direct operation from a battery supply will be dealt with when particular arrangements are under consideration.

(C) *Electric supply taken direct from machine terminals.*—This scheme was at one time very popular with one well-known firm of consulting engineers, the main advantage being that in the event of one of the main generator switches being opened the auxiliary supply is not cut off.

(D) *Electric supply from main alternator via special windings on main transformers.*—This system has been adopted on sets Nos. 3, 4 and 5 at the Dalmarnock station of the Glasgow Corporation.

The arrangement is only suitable for a station in which the step-up transformers are directly coupled to their respective turbo-alternators, and the switching is carried out on the high-voltage side. There would appear to be much in favour of this scheme, and it will be of great interest to learn what is the opinion of the Glasgow Corporation after it has been in operation for a year or two. If this arrangement proves to be satisfactory, the possibility of obtaining the auxiliary supply in this way should be considered as an important factor when the choice between switching on the low-tension or high-tension side of the main transformers is under consideration.

(E) *Electric supply from special house set.*—This is undoubtedly the most popular system of auxiliary electric supply in this country, but there is considerable diversity in the disposal of the exhaust steam from the house turbine (or engine).

This steam may be taken :—

(*a*) To atmosphere.
(*b*) To a stage of the main turbine near the exhaust end.
(*c*) Direct to the condenser of the main turbine.
(*d*) To a feed heater.
(*e*) To its own condenser.

(*a*) Direct exhaust to atmosphere is uneconomical and very wasteful of water, but is simple. For emergency use it is worthy of consideration.

(*b*) The disadvantages of exhausting to a stage of the main turbine near the low-pressure end have already been mentioned.

(*c*) Exhausting to the main condenser suffers from the same disadvantages as exhausting to a stage near the low-pressure end of the main turbine.

(*d*) Exhausting to a feed heater is a system which has been installed in several recent American power stations. As the purpose of a house turbine is not to feed-heat, but to generate power for the auxiliaries, and as the use of steam bled from the main turbine for feed-heating has been found to be both economical and satisfactory in working, it would appear advantageous to dissociate the house set from the duty of feed-heating. In the American stations to which reference has just been made, very elaborate arrangements are installed to vary the load on the house set so that it produces an amount of exhaust steam sufficient to keep the feed water heated to a constant temperature, and it would seem that the introduction of these devices materially increases the complication of the auxiliary system, and at the same time reduces reliability.

(*e*) A house set exhausting to its own condenser gives an arrangement which is efficient and self-contained but somewhat complicated and, whilst it has many advantages, it entails an increase in the amount of running machinery in the station, a feature to be avoided as far as possible. This scheme may also entail an increase in the station staff.

Whether one house turbine is installed for the auxiliaries of each main set (as is adopted for sets Nos. 1 and 2 at Dalmarnock), or whether one house set is installed for the whole station, is largely a matter of opinion. In the case of a station in which for long periods only one main turbo-alternator is on load, one house set per main turbine would possibly be more economical in steam consumption, but on the other hand the capital cost of this proposition is much greater than that of the other, and the authors are of the opinion that, where house sets are adopted, it is better to have two per station, one on load and the other for stand-by purposes.

(F) *Special generator on the main alternator shaft.*—This is a comparatively recent proposal and appears to have much to commend it from the operating point of view, as the supply from it is totally independent of any faults on the main supply and the only possible source of trouble is internal.

Whether it should be a.c. or d.c. is open to discussion. If d.c. it would be run in parallel with the other d.c. plant and the battery which is available for emergencies, and of course a certain number of d.c. auxiliary motors with the advantages previously mentioned are required ; if a.c. it could no longer be used directly in parallel, but a simpler machine results and it is a question for the manufacturers as to whether a d.c. generator, of say 300 kW and 3 000 r.p.m. in the case of a 16 000 kW turbo-alternator and of 450 kW at 1 500 r.p.m. in the case of a 25 000 kW turbo-alternator, could be satisfactorily constructed.

The excitation of an a.c. generator is a matter of consideration. It might be excited in parallel with the main alternator but, in view of the facts that main field rheostats are now practically obsolete, and that voltage regulation is carried out by adjustment of the exciter field, it will be necessary either to have a special field rheostat for this alternator or to allow its voltage to vary with the alterations in the exciter field, due to the action of the automatic voltage regulator which is governed by the main busbar voltage.

As an alternative, the excitation current of the special alternator may be drawn from the battery. This is perhaps the best way.

### (3) Consideration of Different Combinations of Auxiliaries and Supplies under Various Conditions of Working.

*Conditions of station.*—In addition to the internal arrangements, the conditions of the station must be taken into account when the auxiliaries are being decided.

Stations may be divided into the following classes :—

(1) Isolated, supplying an area or an individual works.
(2) One of several stations supplying an area, but not permanently linked up.
(3) One of several stations supplying an area, and permanently linked up.
(4) A station used as a stand-by (usually to a hydro-electric supply).

In the case of a station of Type (1) or (2), the arrangement of auxiliaries depends upon the importance of continuity of supply. For instance, where the station supplies a works with a large number of interlinking processes, continuity of supply is of primary importance, and in such a case it is essential to see that this continuity is not prejudiced through false economy in the lay-out of the auxiliary arrangements. In this country the continuity of electric supply for public service is considered highly important, to a much greater degree than in some other countries, and the public supply engineer must take every care to provide for it.

The various auxiliary supplies discussed in Section 2 can best be compared by the examination of definite schemes for a station supply, these schemes containing alternative combinations of the different supplies. With this object a number of arrangements, drawn out with the view to showing possible rather than recommended proposals, have been put forward by the authors, and the electrical connections will be found in Figs. 1 to 7.

*Basis of alternative schemes.*—These are designed for a station containing five 25 000-kW turbo-alternators, of which four would be required for maximum load.

Steam would be obtained from four boiler houses, one boiler house supplying full-load steam for one turbine.

Each boiler house would contain six boilers, five of which would be required for the maximum output of one turbine. This allows one boiler per group always to be laid aside for cleaning.

Each turbine has two separate circulating pumps, each with its own motor, and two air and two extraction pumps, there being two motors for these, each motor driving one air and one extraction pump. An alternative is to drive each air and extraction pump by its own motor, but if each of these pumps is to be in duplicate this necessitates four motors instead of two and providing the speed of the pumps is suitable, the arrangement put forward appears to be less expensive and equally reliable.

It will be seen that, generally speaking, each set of turbo auxiliaries is independent of the others, so that it can be treated as a unit; similarly, the group of boilers required for one turbine forms a unit which is independent of the others, although in emergency any boiler group can be used to supply steam to any turbine.

*Arrangement of condenser auxiliaries.*—The use of two circulating, two air and two extraction pumps is, from considerations of design, practically essential for 25 000-kW sets, but for smaller sizes of turbo-alternators the case is different, and one very usual scheme is to have two circulating pumps for the condensers of two turbines, each pump capable of supplying circulating water for one condenser, but running in parallel on the *water side*, so that in the event of failure of one pump it is certain that each condenser will have a supply of cooling water adequate to maintain a considerable percentage of the normal vacuum until such time as the trouble can be rectified or one of the turbines shut down. The two pump motors are fed from independent sources, and valves are installed as shown in Fig. 8, for the isolation when necessary of either pump, all these valves being open under normal working conditions.

The main drawback to this proposal is that to obtain a duplicate auxiliary supply it is essential either to run the turbines always in pairs, or for one turbine to run pumps of twice the necessary output.

At this stage it may be of interest to consider a scheme adopted in some American stations of having the boiler-house auxiliaries direct steam-driven, and installing a special d.c. generator for the condenser auxiliaries. This generator is driven at one end by a turbine exhausting to a feed heater, and at the other by an a.c. motor fed from the main busbars. Undoubtedly this gives for the turbine auxiliaries a drive which is unaffected by faults on the main busbars, but, in view of the possibility of failure of the generator, it does not secure absolute duplication of auxiliary supply. It is understood that such an arrangement is installed also for the purpose of regulating the feed temperature. Where it is adopted, care must be taken so that in the event of a fall in frequency of the main supply there is no danger of the motor on the generator shaft acting as a generator and overloading the driving turbine at the other end to such an extent that it is endeavouring to carry the whole station load.

*Basis of powers for auxiliary motors.*—The powers given for the various auxiliary motors are based on the assumption that the station is a riverside station, with a syphonic circulating system. If it were a cooling-tower station, the circulating-pump powers would be approximately doubled, but the air-pump powers would be lower because of the lower vacuum. Ejectors may, of course, be installed instead of the air pumps, but the choice between these alternatives is outside the scope of this paper.

*Details of auxiliaries.*—The boiler-feed arrangements are the same in all the schemes, each boiler house containing one electrically driven feed-pump and one steam-driven (turbo) feed-pump, either of which is capable of supplying the whole boiler house, and both are always available for immediate use. In addition, the feed systems of the individual boiler houses would be interconnected, so that practically any feed-pump would be available for any boiler in case of emergency.

Six motors are provided for the stokers of each boiler house, but only three, each of 10 h.p., are required at any one time, the other three being available for immediate use by the operation of clutches.

Except for the stand-by feed-pump, steam-driven auxiliaries have not been considered, because the authors are of the opinion that any extra economy obtained by their use is not a sufficient return for the additional attention which they require as compared with motor-driven auxiliaries; further, their use necessitates a considerable increase in the boiler feed make-up.

Where a.c. motors are shown it is intended that, as previously mentioned, regulation should be obtained :—

(*a*) For stokers, by variable-speed gears.
(*b*) For pumps, by valves.
(*c*) For fans, by dampers.

*Feed heating.*—For the reasons given on page 832, feed heating by steam bled from the main turbines has been assumed in all the schemes, and the interlinking of feed heating with the use of steam from auxiliaries has not been considered.

*Main busbar voltage.*—In all cases except No. 5 it has been assumed that the main alternators will be connected to 6 600-volt busbars, and that if a higher voltage is used for transmission the necessary step-up transformers will be placed on the feeder side of the main switchgear. Some of these schemes can, however, be utilized equally well if each machine forms one unit with a transformer, as shown in Scheme 5.

*Sectionalizing of main busbars.*—It has been assumed that the busbars will be in four sections, and that the high-tension system is also in four sections, coupled only at the main station and not at the substations; details as to the tying of these sections, whether by reactances between the sections, or by a tie bar with reactances, or by reactance in the generators, are outside the scope of the paper. For simplicity a purely diagrammatic arrangement has been shown in the figures.

It will also be noted that in each scheme a sub-busbar at the main busbar voltage has been provided. This bar is divided into sections similarly to the main bar, each section being fed from the corresponding section of the main bar.

Switches would be inserted between the various sections of the sub-busbar. These, however, are only for use in emergency or when cleaning, and may be of much smaller breaking capacity than the switches coupling the sub-busbar to the main busbars. They must normally be left open, as closing them would be equivalent to paralleling the sections of the main busbar without even the protection of the reactance that results from the cable between a substation and the main busbars.

The authors would suggest that the control of the switches feeding the sub-busbar and of those sectionalizing it should be in the main high-tension control room of the station, the mimic bar on the main board including a section showing the sub-busbar.

By this means, the possibility of an error in switching on the high-tension side of the station auxiliary system would be reduced to a minimum.

*Oil switches.*—In drawing up the alternative schemes the authors have endeavoured to keep to a minimum the number of oil switches on the main busbars, because every switch on the main bars must obviously be capable of breaking the whole capacity of the section of the busbars to which it is connected.

*Synchronous and asynchronous motor-generators.*—Synchronous motor-generators have only been put forward where it is necessary to provide for feeding the a.c. bars from the d.c. bars.

In all other cases induction motors are proposed because they are much less likely to trip out at times of fault on the a.c. supply, and they can also be started much more readily.

Similarly, rotary converters have not been proposed except for one of the schemes, as for auxiliaries the greater reliability of the supply from motor-generators at times of disturbance more than balances their lower efficiency as compared with rotary converters.

*Isolation of station.*—These schemes all assume a station which is not interconnected with any other supply. Under modern operating conditions this is rather improbable for a station of the size considered, but has been taken as a basis because of the fact that, under fault conditions, virtual isolation may well occur.

*Starting-up a dead station.*—In the event of a station being absolutely dead, i.e. with all fires out, it is interesting to note that even with the modern short chimney it would be quite possible to raise steam by natural draught in a reasonable time to get one turbine running. This means that it is not essential to install a battery of sufficient size to carry the load of the boiler house fans during the starting-up period, but it must be adequate to supply current to the stoker motors.

One forced-draught fan supplies two boilers and, as a slight modification of the arrangements shown in the figures, it is well worth considering the advisability of feeding the induced-draught fan motors of each pair of boilers from one supply, and feeding the forced-draught fan motor of the same pair of boilers from the other, so that a failure of either auxiliary supply will not deprive any of the boilers of all artificial draught at times of peak load when both forced and induced draught are in use.

*Changing-over a.c. supplies.*—In changing-over a motor from one a.c. supply to another it has been found by experience that, even with a change-over switch designed to act with the least possible loss of time, the ensuing kick on the motor often causes breakage of the coupling bolts.

In some cases where it is desired to change a motor from one supply to another which is in phase with it, there would be no objection to the temporary paralleling of these supplies at the motor, but for the danger which would be present if they were left coupled.

It would therefore be interesting to have the opinion of switchgear engineers as to the possibility of a time-lag interlock, so that in changing-over from one supply to another the supplies could be paralleled for a specified period, say 30 seconds, after which the first supply would automatically be cut off.

*Parallel supplies.*—Where supplies to an auxiliary busbar are in parallel, as in the case of the d.c. generators in Scheme 1, it is to be understood that suitable reverse-current relays would be included to prevent the other supplies feeding-in to any generator that may become faulty. For the sake of clearness, such refinements have been omitted from the figures.

*Conveyer motors.*—It will be noted that the schemes put forward deal only with the supplies to motors coming under the first three groupings given on page 830, and that no provision is made for the supply to conveyer motors and the other machinery under group (*d*).

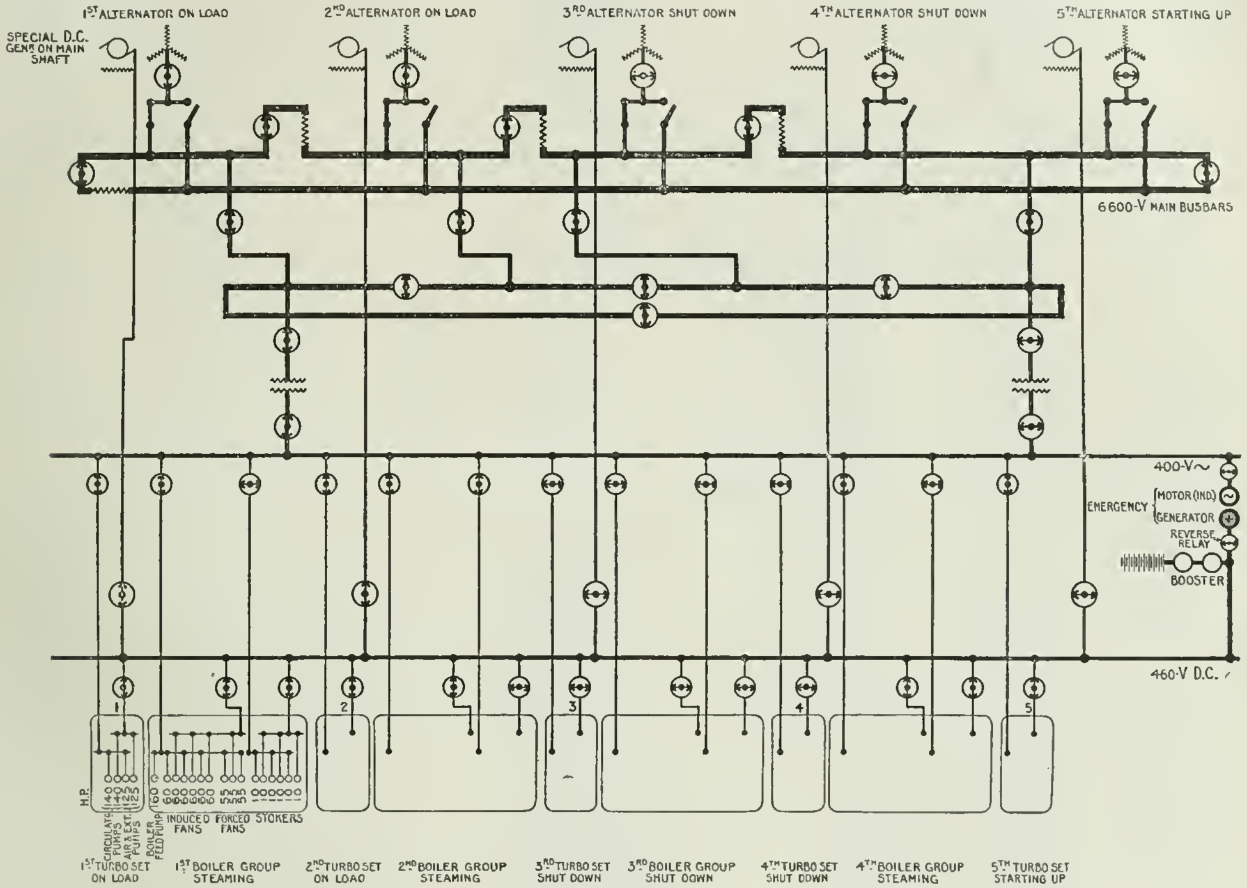


FIG. 1.

As these latter motors may stop for periods up to about 12 hours without shutting down the station, no special provision need be made for an instantaneous duplication of their supply, and it is intended that they should receive their supply from a house service busbar, fed from the main busbars by either a transformer or motor-generator, according to whether they are a.c. or d.c. In certain of the schemes this may be one of the busbars which supply turbine auxiliary motors, etc., but to avoid complication of the figures all such motors have been left out.

*Representation of switches in diagrams.*—It should be borne in mind that the method adopted for indicating switches in the figures is not intended to specify the type of switch, and therefore does not differentiate between the oil-break and air-break patterns.

### SPECIAL NOTES REGARDING INDIVIDUAL SCHEMES.

*Scheme* 1. *Special d.c. generator on shaft of main turbo-alternator* (see Fig. 1).

*D.C. generators.*—These generators would be self-excited, and reverse-current relays would be required between them and the d.c. busbar to prevent any possibility of motoring. They are not intended to supply current for the excitation of the main alternators, this being obtained from the usual type of exciter mounted on the main shaft, or from separately driven exciters if this latter method is preferred.

*General features of scheme.*—In many respects this scheme is similar to Scheme 6, but, as the possibility of total failure of auxiliaries is less, the size of the battery may be considerably reduced. The maintenance required would be fairly great because of the large number of d.c. motors, and a considerable number of spares would have to be carried, as both a.c. and d.c. motors are employed. However, there is much to commend in the scheme if the d.c. generator can be considered

## COMPARISON OF SCHEMES.

| | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 5 | Scheme 6 | Scheme 7 |
|---|---|---|---|---|---|---|---|
| | | | **Source of Supply.** | | | | |
| (A) Turbine aux. motors. | Half a.c. and half d.c.<br>A.C. fed from 400 V aux. busbar supplied from main H.T. busbar via aux. transformer. D.C. fed from 400 V busbar supplied by special generators on main turbo-alternator shafts. | All a.c.<br>Divided between two 400 V aux. busbars each supplied from main H.T. busbar via aux. transformer. | All a.c.<br>Half supplied directly from special 400 V generator on shaft of turbine to which they belong. Half fed from 400 V busbar supplied from main H.T. busbar via aux. transformer. | All a.c.<br>Half supplied direct from special 400 V generator on shaft of turbine to which they belong. Half fed from 400 V busbar supplied from main H.T. busbar via aux. transformer. | All a.c.<br>Half supplied direct from special winding on main step-up transformer of turbo-alternator to which they belong. Half fed from 400 V busbar supplied from main H.T. busbar via aux. transformer. | Half a.c. and half d.c.<br>A.C. fed from 400 V ringed busbar supplied from main H.T. busbar via aux. transformer. D.C. fed from 400 V busbar supplied from main H.T. busbar via M.G. set. | All d.c.<br>Divided between two 460 V (or 230 V) busbars, either of which may be supplied direct from either of two condensing house service turbo-generators or from main busbars via either of two M.G. sets. |
| (B) Boiler house fan motors. | Partly a.c. and partly d.c.<br>A.C. fed from busbar which supplies turbine a.c. aux. motors. D.C. fed from busbar which supplies turbine d.c. aux. motors. | All a.c.<br>Divided between busbars which supply turbine aux. motors. | All a.c.<br>Divided between busbar which supplies half of turbine aux. motors, and 400 V busbar supplied from main H.T. busbars via (another) aux. transformer. | All a.c.<br>Half supplied from special 400 V generator on shaft of turbine which is receiving steam from boiler group to which they belong. (See description of special change-over switch in text.) Half supplied from 400 V aux. busbar referred to for turbine auxiliaries. | All a.c.<br>Half supplied from special 400 V winding on main step up transformer of turbo-alternator which is receiving steam from boiler group to which they belong. (See description of special change-over switch in text.) Half supplied from 400 V aux. busbar referred to for turbine auxiliaries. | Partly a.c. and partly d.c.<br>A.C. fed from busbar which supplies turbine a.c. aux. motors. D.C. fed from busbar which supplies turbine d.c. aux. motors. | All d.c.<br>Divided between busbars which supply turbine auxiliaries. |
| (C) Stoker motors. Six stoker motors are shown for each boiler house, three being on load and three for stand-by, the change-over to be effected by the suitable operation of dog-clutches. | Three a.c. and three d.c.<br>A.C. fed from busbar which supplies turbine a.c. aux. motors. D.C. fed from busbar which supplies turbine d.c. aux. motors. | All d.c.<br>Motors on load supplied from 230 V working busbar, which is fed from one of the 400 V aux. a.c. busbars via M.G. set. Stand-by motors supplied from 230 V emergency busbar which is fed from battery. | All d.c.<br>Motors on load supplied from 230 V working busbar, which is fed from one of the 400 V aux. a.c. busbars via M.G. set. Stand-by motors supplied from 230 V emergency busbar which is fed from battery. | All d.c.<br>Motors on load supplied from 230 V working busbar which is fed from 400 V aux. a.c. busbar via M.G. set. Stand-by motors supplied from 230 V emergency busbar which is fed from battery. | All a.c.<br>Fed from same alternative supplies as fan motors of same boiler house. | One group of three a.c. and other group d.c.<br>A.C. group fed from busbar which supplies turbine a.c. aux. motors. D.C. group fed from busbar which supplies turbine d.c. aux. motors. | All d.c.<br>Motors on load fed from one aux. busbar, and stand-by motors fed from other busbar. |
| Battery. | One installed as stand-by to d.c. aux. supply. | One installed for supplying stand-by stoker motors. | One installed for supplying stand-by stoker motors. | One installed for starting auxs. of first turbine in dead station, and for supplying stand-by stoker motors. | None. | One installed as stand-by to d.c. auxiliary supply. | One installed as stand-by to either of the two d.c. aux. supplies. |
| Arrangements for battery charging. | From 400 V a.c. aux. busbar via M.G. set. | From either of two 400 V a.c. aux. busbars via M.G. set. | From either of two 400 V a.c. aux. busbars via M.G. set. | Via M.G. set, from 400 V aux. busbar, or in emergency from special a.c. aux. generators. | — | From subsection of main H.T. busbar via M.G. set. | Direct from either of the d.c. aux. busbars. |
| | | | **Starting up of First Set in Station (assuming Station not interconnected with any other Source of Supply).** | | | | |
| (*a*) Draught. | D.C. fan motors supplied from battery. No supply being available for a.c. fan motors, boilers dependent on these must use natural draught. | Natural draught must be used. | Natural draught must be used. | For details of starting up, see text. | For details of starting up, see text. | D.C. fan motors supplied from battery. No supply being available for a.c. fan motors, boilers dependent on these must use natural draught. | Natural or artificial, according to size of battery. |
| (*b*) Stokers. | D.C. motors used at this stage, supplied from battery. | Motors supplied from battery. | Motors supplied from battery. | — | — | D.C. motors used at this stage, supplied from battery. | Motors supplied from battery. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (*c*) Turbine aux. motors | D.C. motors used at this stage, supplied from battery. | With arrangement of M.G. sets as shown, turbine would have to be started up to atmosphere. | With arrangement of M.G. sets as shown, turbine would have to be started up to atmosphere. | — | — | D.C. motors used at this stage, supplied from battery. | Motors supplied from battery, or house set may be run up (either to atmosphere or with its auxiliaries supplied from battery) and connected to aux. busbar. |

### Starting up of Second and Succeeding Sets in Station.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Either a.c. or d.c. motors may be used as found convenient. If d.c., care must be taken to avoid overloading the d.c. generators which are already running. As soon as each main alternator is switched in, its aux. d.c. generator should be switched on to the d.c. aux. busbar. | Supply obtained from aux. a.c. busbars. As soon as the second main alternator is switched in, the second aux. transformer should be switched in, being connected to a section of the main busbars (H.T.) different from that feeding the first aux. transformer. | Supply obtained from a.c. aux. busbars, but until each main turbine is run up to speed only half its auxiliaries can be utilized. This may be a severe drawback if main turbo-alternator is required on load urgently. The second aux. transformer to be switched in as in Scheme 2. | For details of starting up, see text. | For details of starting up, see text. | Either a.c. or d.c. motors may be used as found convenient. | All the aux. motors are available. |

### Effect of Fault; One Set only on Load.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Possibility of failure of a.c. and d.c. supplies at once is very remote. If it did occur, battery could be used to keep turbine aux. motors running until set is shut down. | When only one main turbo-alternator is on load, there is no real duplication of supply except to stoker motors. The switching in of the second aux. transformer at this stage would protect the supply against failure of transformer, but not against fall of voltage on main H.T. busbars. | A fault on the main H.T. busbars would shut down all boiler house fan motors, but the possibility of total failure of turbine aux. supply is very remote. | A fault on the main busbars would shut down half turbine auxs. and half fans, but possibility of total failure is very remote. | There appears to be some possibility of a fault on the main H.T. busbars shutting down all the aux. motors, but the exact effect on the aux. supply is a matter of doubt, and, pending further information, it is difficult fully to discuss and assess this scheme. | In the event of a fault on main busbars, battery would be used to keep turbine aux. motors and stoker motors running, but the running of the d.c. fan motors would depend upon the size of battery installed. | It is intended that normally one aux. busbar should be supplied from a M.G. set, and the other from a house turbo-generator, the battery being coupled to the latter bar. The possibility of failure of M.G. set and house set at the same time is very remote, but should it occur the battery would keep the turbine auxiliary and stoker motors running, and, if installed of sufficient capacity, the fan motors also. |

### Effect of Fault; Two or more Sets on Load.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | In event of failure of a.c. supply, d.c. generators would keep all d.c. motors running. In event of failure of one d.c. generator the d.c. supply would be maintained by other generators and battery. | Assuming that reactances are inserted between various sections of the main busbars, it is doubtful if any fault would cause both auxiliary supplies to fail, always provided that the interconnecting switch between the auxiliary busbars is open, as it should be on normal running. | Remarks given in case of one set apply here also. | Remarks given in case of one set apply here also. | Possibility of loss of vacuum or of shut-down of station due to auxiliary failure is very remote. | Assuming that reactances are inserted between various sections of the main busbars, it is doubtful if any fault would cause both aux. supplies to fail. The installation of a battery of sufficient capacity to carry on the d.c. auxiliaries of the station in such an emergency would be very expensive. | Remarks given in case of one set apply here also. |

### Suitability of Scheme for Station with 33 000-volt Busbars (assuming that Step-up Transformers form Units with Main Alternators).

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Equally suitable | Equally suitable. | Equally suitable. | Equally suitable. | Suitable only for station with 33 000-volt busbars. | Equally suitable, but step-down transformer would be required for a.c. side of M.G. set. | Equally suitable. |

to be a reliable proposition. The views of manufacturers in regard to these points are invited, especially in view of the modern tendency towards turbo-alternators of large outputs running at 3 000 r.p.m. Commutation would probably be the greatest difficulty and it is assumed that the radial type of commutator would be essential for a 3 000 r.p.m. set.

To rectify any minor trouble occurring with any d.c. generator without shutting down the main turbo-alternator, the troublesome generator would be switched off the bar, the d.c. supply being maintained by the other generators, which would each carry a larger load than usual, the battery and motor-generator assisting if necessary.

It would probably be advisable to carry one spare d.c. generator in the station, or at least a spare armature suitable for any of the auxiliary d.c. generators.

*Scheme* 2. *Two auxiliary a.c. busbars, each fed by transformer* (see Fig. 2).

*Interconnector on auxiliary busbars.*—An interconnecting switch is provided between the two 400-volt a.c. busbars, so that in the event of either transformer being out of action all the a.c. motors could be fed from the other transformer.

As, however, to operate under these conditions would mean the sacrifice of the duplication of supply, it is a question as to whether an additional transformer should not be carried for use in such emergencies.

*Alternative arrangement of motor-generators.*—In view of the fact that, with the arrangements shown in Fig. 2, it would be necessary to start the first turbine of a " dead " station to atmosphere as the station does not form one of an interconnected system (or even in the event of there being an interconnector, if this is out of action), it would be highly desirable to have at least one of the motor-generators of the synchronous type, so as to be reversible, thus dispensing with reverse-current relays on the d.c. side, and have the battery of sufficient output to carry the load of one set of turbine auxiliaries.

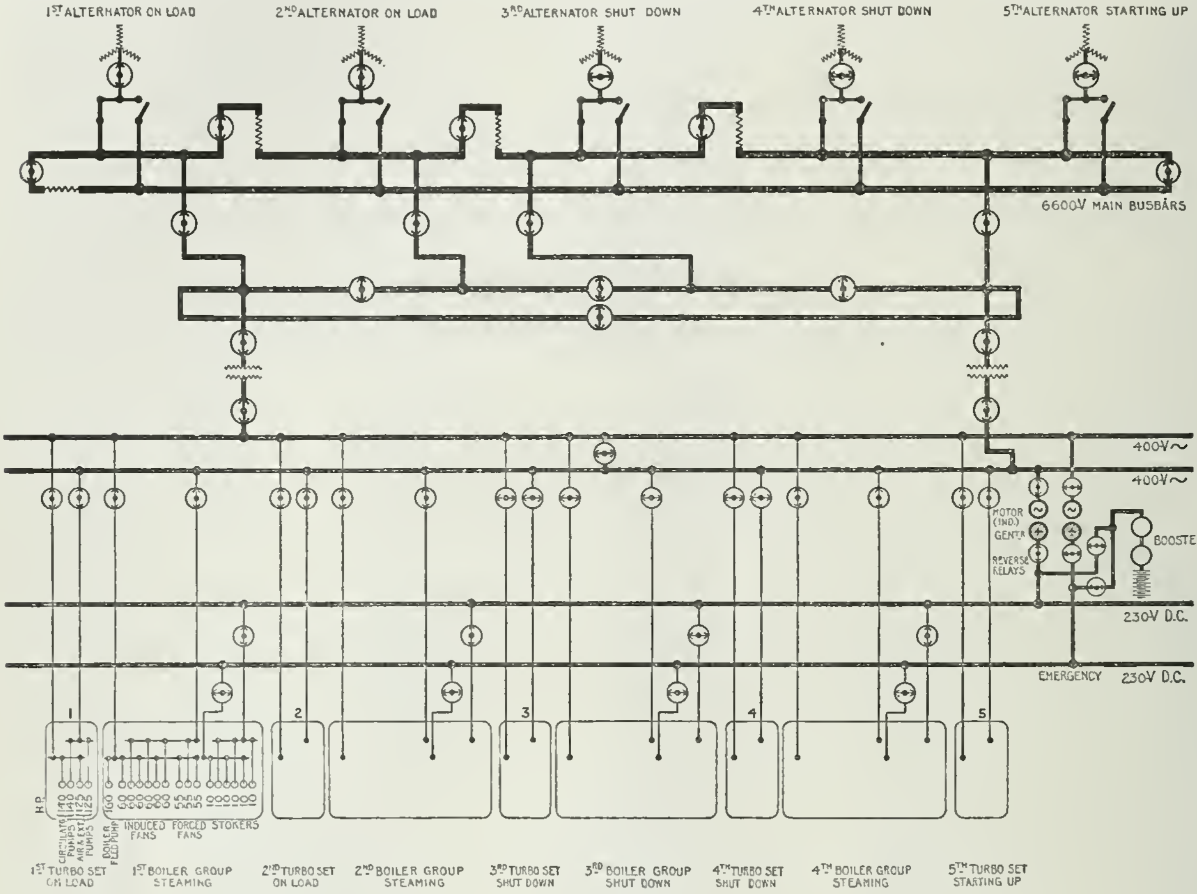


Fig. 2.

*General features of scheme.*—This arrangement is simple in operation, efficient and does not require a considerable amount of maintenance, and the spares required would be a minimum.

Where continuity of supply is very important, it is questionable as to whether this scheme can be considered to be really satisfactory.

*Special type of house turbine.*—The following arrangement of house set may be considered to be especially suitable for this scheme, and may increase the reliability of the auxiliary supply.

The house set to be of the simplest possible character, exhausting to atmosphere, and to be connected up so that the pressing of a button on the switchboard would enable the set to be on the bars within, say, 10 to 15 seconds. This would be effected by having a motor-operated steam stop-valve, the pipe line being so designed as to be continuously drained. The lubrication arrangements would require special consideration.

As soon as the set approached full speed the governor would automatically put the generator on the busbars through a reactance, and one or two seconds later would short-circuit the reactance. The mechanical shock due to this switching would be severe, but the set would be designed to withstand it.

By this means, in the event of the switchboard attendant observing a failure of supply on one of the auxiliary bars, he could run up the house set and switch off the faulty supply, with a reasonable chance of saving the motors on that auxiliary bar from being shut down.

*Scheme 3. Special a.c. generator on shaft of main turbo-alternator, for turbine auxiliary motors only* (see Fig. 3).

*Starting-up of first set in station.*—As stated in the table, for starting up from a "dead" station it would be necessary in this scheme to run to atmosphere the first turbine to be put on load, but if, *before starting*, the auxiliary generator were switched on to the motors which it normally feeds, these motors would run up to speed with the generator and it appears possible that a vacuum might be obtained sufficiently quickly to avoid any distortion troubles in the main turbine.

It would be interesting to have the opinions of turbine designers on this point, and also to know whether the provision of an air ejector to assist the air pump would help matters.

If such a method of starting is not possible, it would be advisable to consider the use of reversible motor-generators as suggested for Scheme 2.

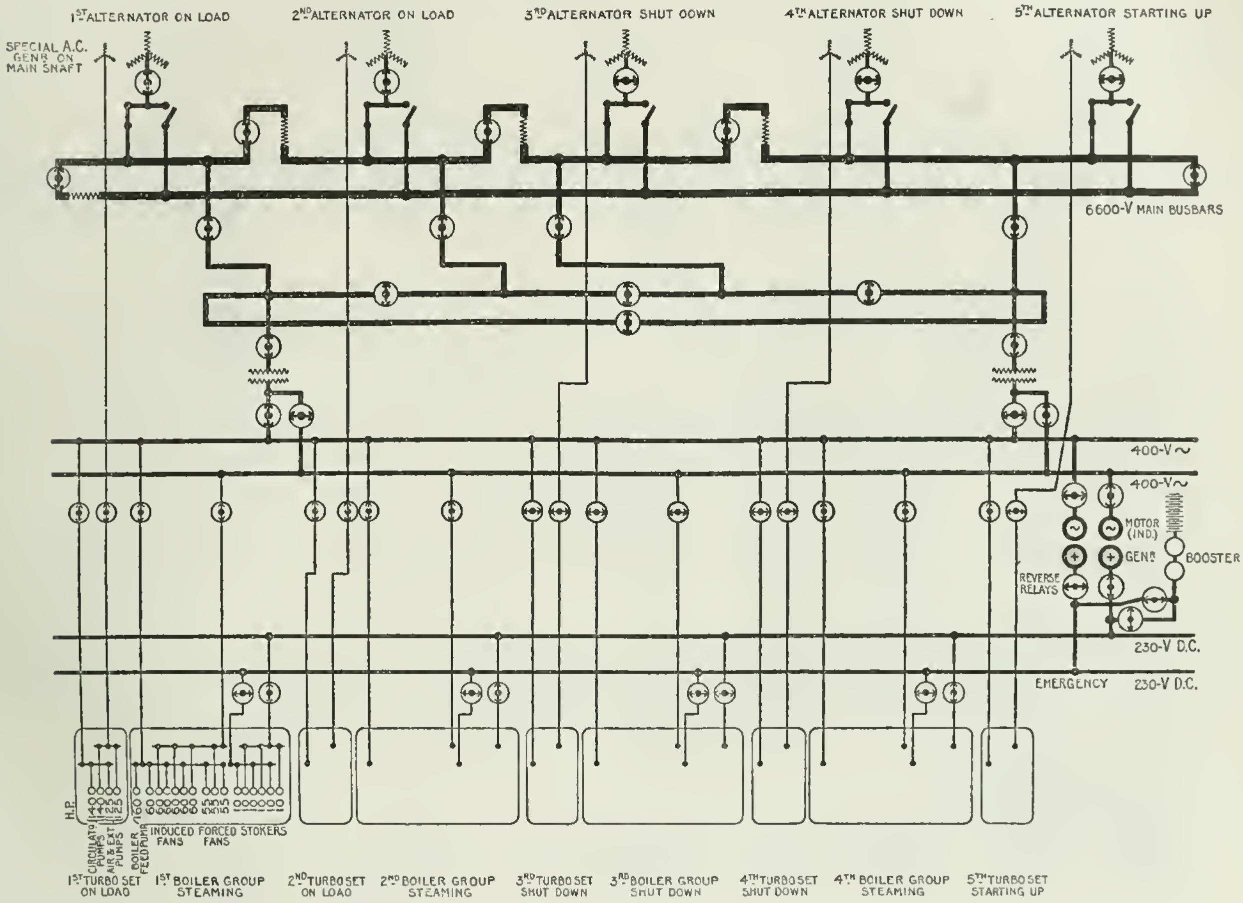


Fig. 3.

*Fault on auxiliary generator.*—In the event of a fault on one of the auxiliary generators, half the auxiliary motors of the main turbine to which it belongs will be shut down until the generator has been repaired or other arrangements have been made.

To obviate this, switches might be installed so that the auxiliaries normally fed from the special generators could, in emergency, be fed from the auxiliary busbar.

In preparing the scheme the authors considered the use of such switches, but as with this arrangement there would be considerable danger of coupling together supplies which are not synchronized, and as the breakdown of the auxiliary generators should be a very remote contingency, it was decided to omit them from the diagram.

*Supply to auxiliary busbar.*—It will be noted, in comparing this with Scheme 2, that there is a slight difference between the methods of connecting the low-tension sides of the auxiliary transformers to the busbars, but neither arrangement appears to have any special advantage over the other.

*General features of scheme.*—This arrangement is simple in operation, efficient and does not require a very considerable amount of maintenance, and the spares required would be a minimum. The special a.c. generator should be more satisfactory in use than the d.c. generator of Scheme 1, and continuity of supply could be relied on to a considerable extent.

*Scheme 4. Special a.c. generator on shaft of main turbo-alternator, for turbine and boiler house auxiliary motors* (see Fig. 4).

*Special change-over switch.*—As it is desired to avoid paralleling the auxiliary generators either with the main supply or with each other, some special switching device will be necessary to carry out the changing over.

For the purpose of the diagram this is shown as a plug board, with six incoming supplies (five from auxiliary generators and one from the battery via a motor-generator) and four outgoing feeders, one to each boiler house.

Open circles represent plug holes, and these are filled in, in black, in the cases where a plug is assumed to be in.

Although this is quite adequate for the diagram, such a construction would not be satisfactory in practice, more especially as there would be three phases to deal with, and the design of such a change-over switch would require very careful investigation.

*Starting-up of first set in station.*—To avoid the necessity of installing a very large battery, it is suggested that steam should be raised under natural draught conditions. The auxiliary a.c. busbar would be energized from the battery by the running-up of the motor-generator which is directly connected to it, and half the turbine auxiliaries would be supplied from this bar.

The main turbo-alternator would now be run up to speed, and would require to be synchronized with the auxiliary a.c. bar (through one of the transformers) before being switched in.

When the turbo-alternator is on the bars, the other half of the turbine auxiliaries may be started up from the auxiliary generator, and the motor-generator run so as to charge the battery.

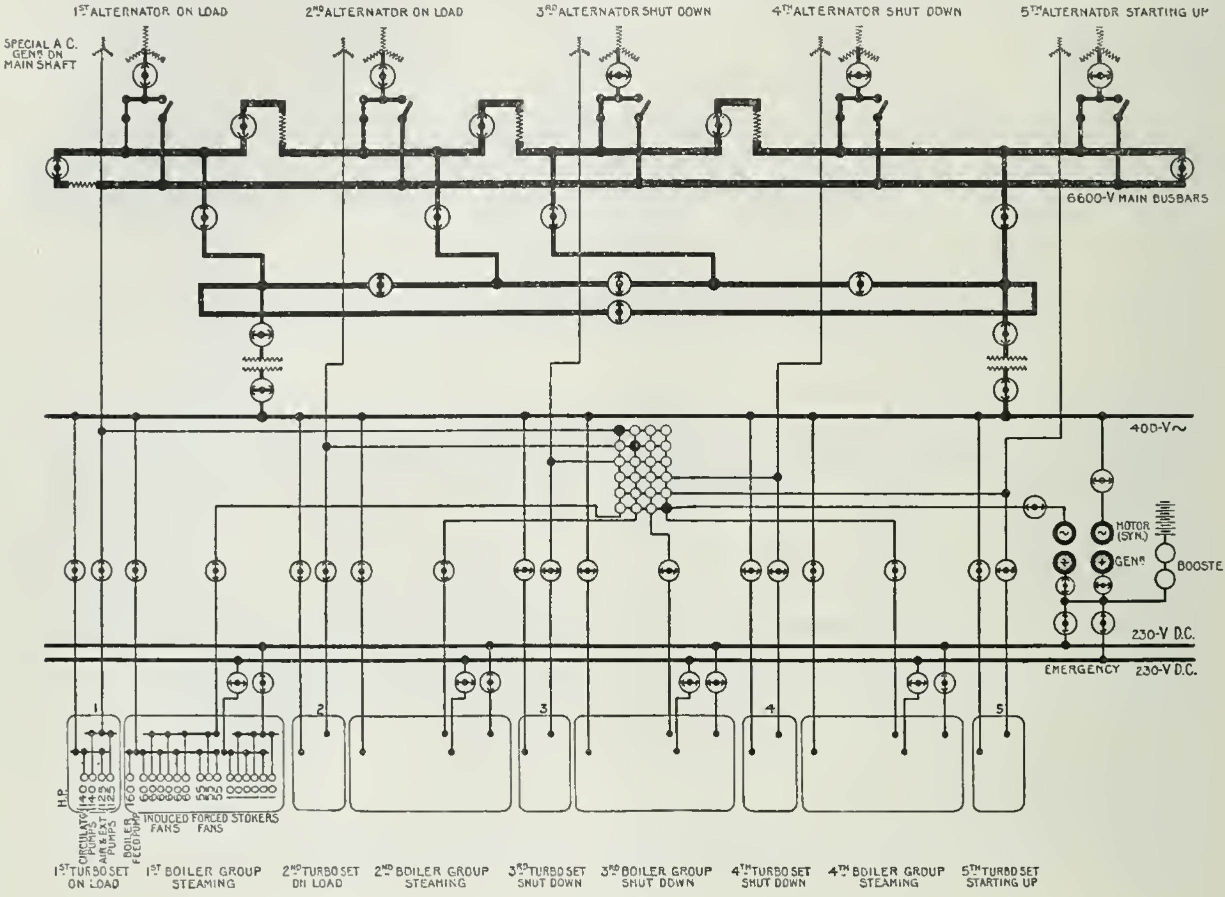


FIG. 4.

The boiler-house fans may now be started up, one group from the a.c. auxiliary busbar, and the other from the auxiliary generator, the change-over switch being suitably operated.

*Starting-up succeeding sets.*—For the starting-up of succeeding sets the boiler-house and turbine auxiliaries fed from the 400-volt a.c. auxiliary busbar will first of all be run up, and the other half of the auxiliaries started up from the supply from the auxiliary generator of the incoming turbo-alternator, as soon as the latter has been switched on to the main busbars.

When two or more sets are running in the station, the second auxiliary transformer may be switched in if it is desired to increase further the reliability of the auxiliary supply.

Great care will at all times have to be exercised with the change-over switch, so that no two auxiliary generators are paralleled and that none of these generators are overloaded.

*General features of scheme.*—This arrangement is efficient, does not require a considerable amount of maintenance, and the spares required would be a minimum. It should be reliable in operation, but there appears to be a great risk of mistakes occurring in the use of the change-over switch and, in addition, this will probably be an expensive piece of apparatus.

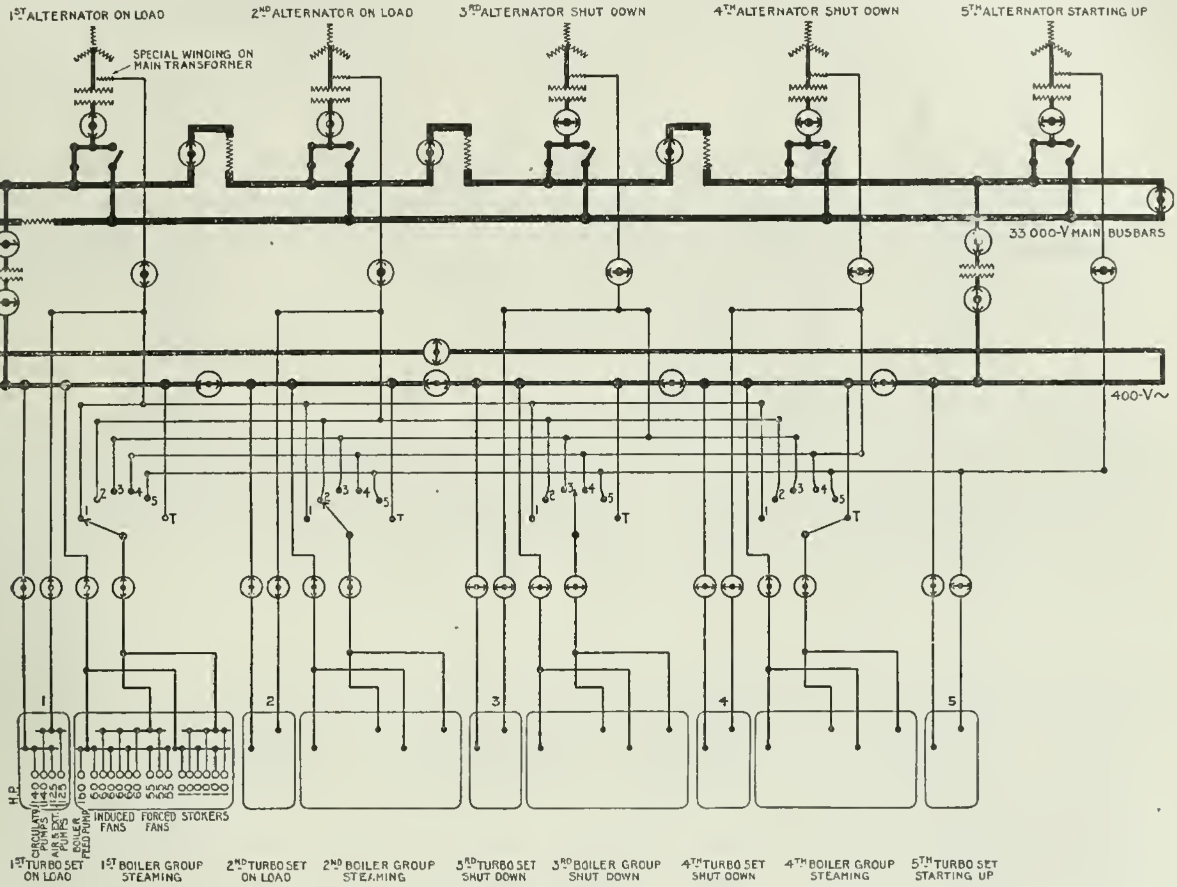


FIG. 5.

*Scheme* 5. *Special winding on main step-up transformer* (see Fig. 5).

*Construction of change-over switch.*—The change-over switch would be in series with an oil switch, with which it would be interlocked, and consequently could be of the air-break type.

Possibly the simplest arrangement would be to have an isolating switch on each phase, with as many contacts as required, the blade hinging on a swivelling pivot in such a manner that it could be drawn out of one contact, swivelled round and closed in to another contact as required.

The switches for the three phases of any one circuit should preferably be adjacent, and coupled by a bar so as to prevent any possibility of the three phases not being closed on to the same circuit.

*Starting-up of first set in station.*—With the scheme as shown, it would appear that it would not be possible to start up the first set without exhausting to atmosphere, unless the auxiliaries could be run up with the main turbo-alternator, as suggested in the description of Scheme 3.

If there is no interconnector to another station and this method of starting is not permissible, a special house set might be installed. As this would only have to run at very rare intervals, there appears to be no reason why it should not be designed for exhausting to atmosphere.

If a house set were adopted it would be necessary to synchronize the main alternator with the auxiliary busbars, but, as an alternative method of getting away, the second half of the auxiliaries could be started up from the special winding after the turbine was up to speed, but before switching the main alternator on to its busbar. In this latter case the other half of the auxiliaries would then be switched off, the house set shut down, the main alternator switched in, the auxiliary transformer closed on to the main busbars so as to energize the auxiliary busbar, and the shut-down auxiliaries then restarted.

*Starting-up succeeding sets.*—In the case of succeeding sets it will, if necessary, be possible to run all the auxiliaries during the starting-up period, half being supplied from the auxiliary busbar direct, and the other half from the auxiliary busbar by way of the contact "T" of the appropriate change-over switch.

*General features of scheme.*—This scheme is efficient, does not require much maintenance, and the spares required would be a minimum. The exact degree of reliability is open to question, but, providing that a fault on the main 33 000-volt busbars does not affect all the auxiliary supplies to such a degree as to shut down the motors fed from them, it may be considered as sufficiently reliable for adoption so long as there is more than one set on load. A certain amount of care will be required in the use of the change-over switches, but these appear to be very much simpler than those used in Scheme 4.

*Scheme* 6. *Two auxiliary busbars, fed respectively by transformer and motor-generator* (see Fig. 6).

*General features of scheme.*—This arrangement would be reliable, simple in operation, flexible and fairly efficient. It would require a fair amount of maintenance, because of the large number of d.c. motors used, and the spares required for the motors would be considerable. As a large battery would be required, the first cost of the scheme would be high.

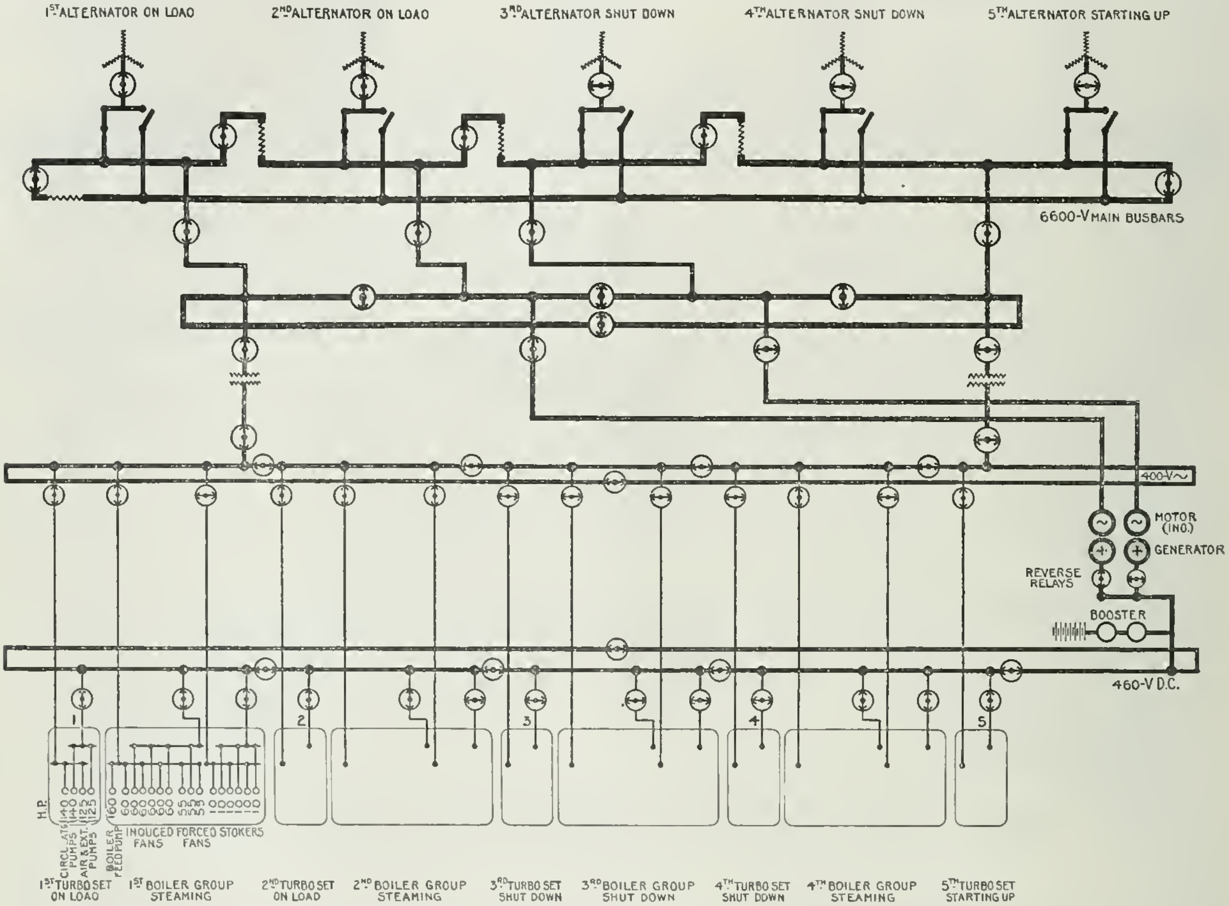


Fig. 6.

*Scheme* 7. *Two d.c. auxiliary busbars, fed respectively from motor-generator and condensing house service turbo-generator* (see Fig. 7).

*General features of scheme.*—The efficiency of this scheme would probably be lower than results when all the auxiliary supply is obtained by the motive power of the main turbines, but on the other hand there are no complications whatever in either starting up or running.

The spares to be carried would be more than where all the auxiliaries are a.c., but less than where they are partly a.c. and partly d.c.

Maintenance would probably be high because of the large number of commutators and brush-gear.

This scheme would be simple to operate and highly reliable, the only drawback being the extra attention required because of the inclusion of a house set.

In apparent contradiction to the remarks on page 834, the authors are of the opinion that in this case rotary converters instead of motor-generators might with advantage be installed, as there is a considerable amount of stand-by plant.

*Running with auxiliary busbars in parallel.*—It is possible that the reliability might be increased if the auxiliary busbars were paralleled by closing the battery on to both bars. By this means the battery would be available as stand-by to both supplies, and the use of reverse-current relays on the d.c. side of the motor-generators and on the lead from the house sets would protect both bars in the event of failure or drop of voltage on either supply.

*Alternative scheme with a.c. motors.*—An alternative scheme, similar to this, in which a.c. motors are used throughout, might be put forward, the motor-generators being replaced by transformers, the house set being a.c., and the battery being fed from the auxiliary busbars by way of reversible motor-generators.

Such a modification would probably reduce the first cost, but would entail additional complications in running, because of the necessity of synchronizing the a.c. supplies at times of emergency, and also because of the probability of any fault shutting down the motor-generators and so rendering the battery of no use at the very time when it is most needed.

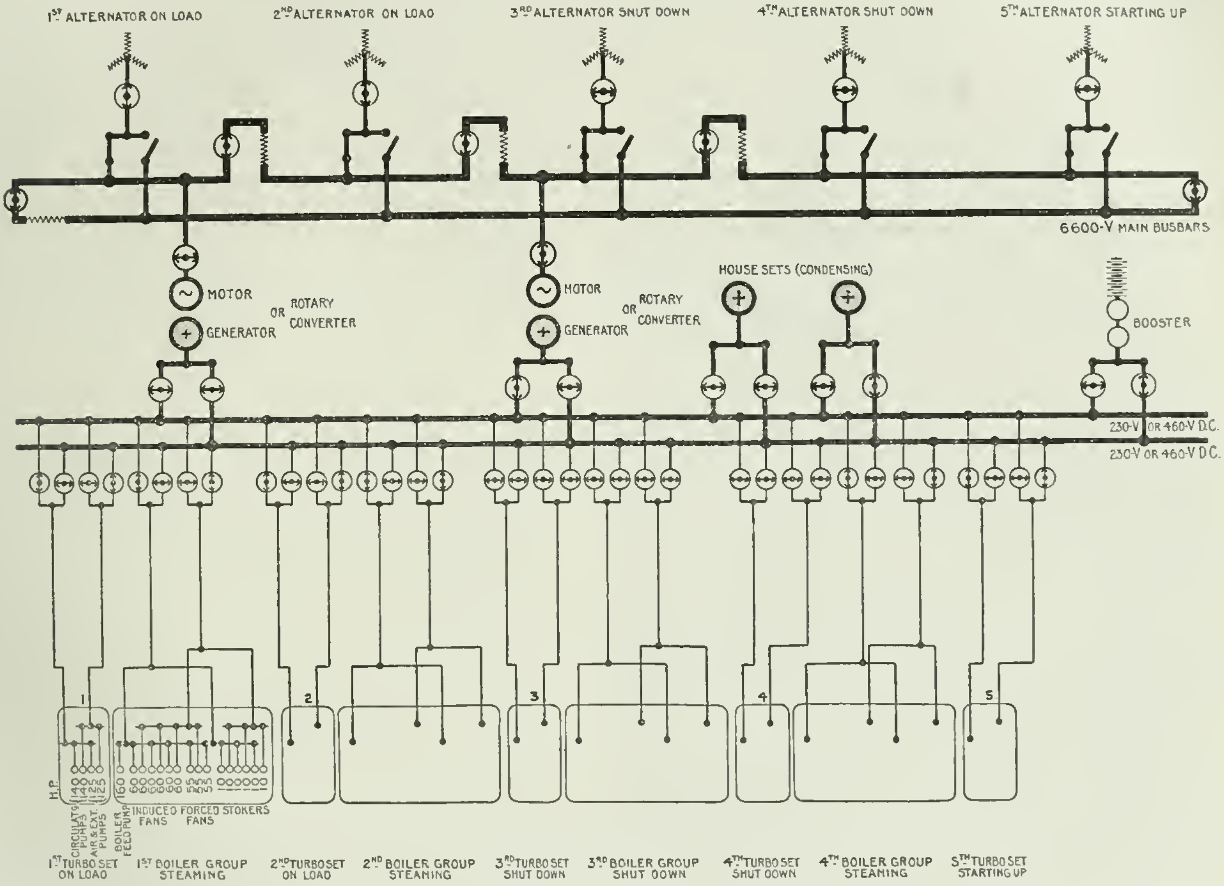


Fig. 7.

### General Consideration of Alternative Schemes.

In considering the relative merits of the foregoing alternative schemes, it must be kept in mind that they are only typical and that it might be advantageous to adopt a combination of some of the alternatives. For instance, where all the supply, except the stoker motors, is shown as a.c., these also might be a.c., although the authors consider that this would be a rather unwise change.

The ring main shown for the auxiliary (400-volt) busbar in Scheme 6 might equally well be adopted in either of the arrangements.

Instead of the d.c. generators of Scheme 1 feeding in parallel on to one bar, they might each feed a separate bar, with an emergency switch to a common-battery bar, so that the battery might, as found necessary, be used for any group of auxiliaries.

With so many combinations to choose from, it is difficult to decide what should be adopted and what discarded, and the authors have endeavoured to put forward a representative selection of schemes, rather than confine attention to what appear to be the most desirable arrangements.

It is also very difficult to come to a decision as to which is the best of the schemes, but on broad lines the authors suggest that they may be graded in three groups, the first and best group containing Schemes 1, 6 and 7, which are of approximately equal merit. In the second group would be Schemes 2, 3 and 5, which although of equal merit one with another cannot be considered as being of the standard of the first group. The third group would consist of Scheme 4, which is an example of what to avoid.

*Details of auxiliaries.*—Once the general scheme of the auxiliaries has been determined, a number of details having a considerable effect on the satisfactory running of the station must be considered.

The switchgear and accessories used for the auxiliary gear of the station should be of the very best quality and design, for it would be unwise to run the risk of breakdown through false economy on plant, the cost of which is only a very small proportion of the total cost of the station. Switchgear for electrical auxiliaries needs careful selection, especially with regard to the protective devices, in order that faults may cause the minimum shut-down, but at the same time to ensure that the protective gear will not operate except in case of faults.

*Choice of voltage.*—Where there are a.c. and d.c. low-voltage circuits in a station, these should be chosen so as both to give the same voltage on lighting circuits. For instance, in the schemes put forward 400 volts a.c. gives 230 volts between one phase and neutral, corresponding to the d.c. voltage of 230.

Considering the choice between the d.c. voltages of 230 and 460, the lower voltage would require only half the number of cells in the batteries, and, although these cells would be larger than in the case of the higher voltage, the reduction in the total number of cells would mean that less lead would be required in the boxes, and this would to some extent compensate for the extra copper required in the connections.

*Station lighting and control circuits.*—In all cases where a battery is not installed for d.c. auxiliaries, a small one would be put in for control circuits, and pilot lights fed from this should be placed at various points in the station, so that any failure in the main lighting supply will not result in total darkness in the station. Two motor-generators, one running and one as a stand-by, should be provided for this control battery.

*Location of switchboards.*—As the drivers should be concerned solely with the starting of motors, the auxiliary supplies should be handled by a special auxiliary switchboard attendant. The auxiliary switchboard should not be far from the main high-tension control board; the high-tension switchboard attendant would thus not be concerned with the details of the auxiliaries in the case of breakdown, except in so far as the auxiliary attendant would receive leading instructions from him.

Auxiliary switchboards controlling duplicate supplies should be symmetrical and as close together as possible.

*Run of cables.*—Whenever possible all the feeders and cables duplicating the supply to any auxiliary should be run by different routes, so that in case of fire or mechanical damage the danger of the supply being cut off from all the auxiliaries would be reduced to a minimum. For example, in the case of the d.c. auxiliaries shown in Schemes 2 and 3, the feeders for the stoker motors should be led by different routes.

*Design of starters and control gear.*—As the motors may have to run without stoppage for periods of several weeks, special care must be taken in the design of starters, control gear, etc., to reduce to a minimum the heating due to resistance losses in conductors or to hysteresis in the ironwork.

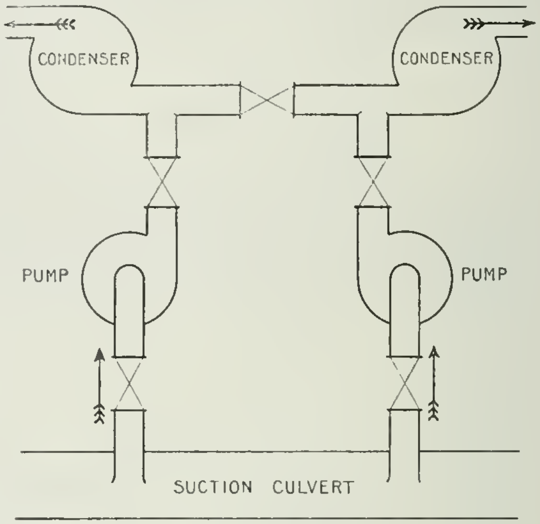


Fig. 8.

The latter feature requires special attention, as apparatus which has been quite suitable for ordinary industrial service has become so hot when used on auxiliary plant for long periods without a break that it has had to be replaced.

*Contactor starting.*—Contactor gear for starting has been adopted in certain cases, but the authors are of the opinion that there is little to justify the extra cost of this, although push-button releases operated from suitably chosen places in the station may be of considerable advantage. For example, a conveyer should have push-button releases provided at intervals along its length, so that the motor can be stopped at once in the event of breakage.

*Location of starters.*—Starters for motors should be placed in very accessible positions and in sight of the moving machinery which they operate.

*Motor operation of valves.*—The use of motors, in addition to hand gear, for the operation of large valves such as those on main circulating pipes, is increasing.

Where these motors are d.c. it is to be noted that they must not be series wound, as a series motor may, once the valve gear is in motion, speed up to such an extent that considerable damage results.

*Brush-lifting gear on a.c. motors.*—Alternating-current slip-ring motors, where used for station auxiliaries, should be fitted with brush-lifting gear, and interlocks should be provided between this, the main oil switch and the rotor resistance, so that the main oil switch cannot be closed unless the short-circuiting gear and the rotor resistance are in their correct starting positions.

*Batteries.*—Batteries may be either regulated by hand-reversible boosters or end-cell regulating switches; in the case of the former, automatic change-over switches should be installed to put the battery directly on the line if the load to be dealt with increases beyond the capacity of the booster.

The choice between the alternative methods is controversial and depends so much on local conditions that it has been decided not to enlarge on it here.

*Operation of auxiliary plant.*—In any scheme in which all the power for auxiliaries is obtained, directly or indirectly, from the main busbars, there is no real stand-by to the auxiliary supply when only one turbo-alternator is running, and in the event of any fault on the main bars there would be a loss of vacuum with its attendant evils.

When there is an interconnector, if only one set is running and for any reason this alternator has to be taken off the bars the wisest procedure, if time permits, is for some of the outgoing feeders to be immediately opened and the interconnector supply used to keep the station bars alive.

At times of light load it is questionable whether many operating engineers would feel justified in running two circulating, two air and two extraction pumps for one turbine. The running of only one of each of these pumps would undoubtedly be more economical, but would mean a distinct sacrifice of reliability.

### CONCLUSION.

The subject under consideration is so extensive that it is difficult to deal with it without becoming involved in a mass of detail, but the authors hope that the method of treatment will be of assistance to those engaged in the laying down of the auxiliary system of a new power station.

They wish to express their thanks to Mr. H. Dickinson for various suggestions embodied in the paper.

## DISCUSSION BEFORE THE INSTITUTION, 26 APRIL, 1923.

**Mr. W. B. Woodhouse:** The paper indicates definitely and well the practical outlook that the operating engineer must take. We have heard in the past, and particularly of recent years, a good deal about station design, and undue emphasis has often been placed on one particular item of production cost. For example, the question of fuel consumption has been unduly emphasized at the expense of other factors of the cost of production, and it is a pleasure to me, as an operating engineer, to read a paper like this, in which the authors very definitely place reliability in the forefront. The question of the design and arrangement of auxiliaries is obviously a complicated one. The authors themselves mention seven different schemes and, after considering them in great detail, put three in the first class. Obviously, therefore, if that is the decision to which they have come after so careful a study of the subject, there is not very much to choose between the different systems. There is no doubt, I think, that the authors' point of view is preferable to that which starts by considering the possibility of an improvement of a fraction of 1 per cent in the heat efficiency of the station. A great many theorists, I think, overlook the fact that if one can design one's coal- and ash-handling plant in an economical way, and save possibly 10 or 20 per cent on the cost of the handled fuel, that means 10 or 20 per cent increase in the commercial heat efficiency of the station. Rather than adopt refinements which may represent a 1 per cent improvement at the expense of reliability or first cost, one should aim, as the authors have suggested, first of all at simplicity. I am very glad, therefore, that they do not over-emphasize the question of heat balance, although it is perhaps rather begging the question when all their schemes are based on the use of steam taken from the main turbines for feed heating. I think that there are other possible schemes. The three factors to be considered are, in the order of their importance, reliability, efficiency, and capital expenditure. It is interesting to note that in two of the three schemes which the authors have placed in the first class it is proposed to use partly direct and partly alternating current, and in the third case direct current only is employed. That being so, I do not think that the authors' criticism of the direct-current motor need be taken too seriously. They mention the difficulties of operating the d.c. motor, but, after all, with modern designs I do not think that one need contemplate having to operate a d.c. motor in a dirty, dusty or otherwise unsatisfactory atmosphere, and experience shows that, in the hands of a competent staff, the d.c. motor is very reliable. The division of the plant and the whole question of reliability is, of course, to a large extent determined by the complete rigidity of connection which alternating current introduces. The authors divide their busbars into sections and consider supplies from other stations, but all the time they have to meet this difficulty, that a disturbance on any one part of the a.c. system is carried immediately to every other part of the system. If we could overcome that difficulty—if these links on the electrical side could be made flexible instead of rigid—the question of station auxiliaries would be very much simplified, and we might come to the conclusion that there was no longer any necessity for steam-driven auxiliaries and consider a system in which all the auxiliaries were of an alternating-current type. There is one other point which I think is worth considering, namely that with the higher steam pressures the disadvantages of the small steam auxiliary increase. One has a number of small steam pipes and drains, and valves, all of which have to withstand the high steam pressure and are subject to leakage, and so, I think, the tendency will be very definitely against a large number of steam auxiliaries. With the large units contemplated by the authors the house turbine becomes a reasonable size, and one could put a high steam pressure on to that and get a fairly efficient result; but for smaller stations it is questionable whether the result would be satisfactory.

**Mr. H. Brazil:** On page 833 the authors say that continuity of supply in this country is considered to be more important than in some other countries, but they might have said "than in any other country." I think that the very high standard of continuity of supply which has been achieved in this country is something that we should aim at preserving. Apart from the loss of prestige which a failure occasions there is another point to be considered, namely, that the loss of revenue is very considerable if a stoppage of the whole system occurs. Roughly speaking, a London supply undertaking shutting down for two hours at a time of heavy load would lose about £1 000 in gross revenue during that period. The consumers would perhaps lose more, because their machinery would be brought to a standstill and their employees, though idle, would still have to be paid. There are other difficulties that would occur if a stoppage took place. To mention only one, the cessation of supply in the case of an ice-making plant might spoil a large batch of ice, as its transparency would be destroyed. The authors have divided the auxiliaries into four types. Type (*a*) consists of those which must not stop on any account, and includes the main circulating-water supply, the air extraction and station lighting. I do not think that there will be any dispute as to the importance of those particular auxiliaries. Under Type (*b*) the authors state that the boiler feed-pump and the power for control circuits must not stop for more than 60 seconds. Here I should like to make a criticism. Those who are used to running a plant, and have experience of getting things straight again after a breakdown, will agree with me, I think, that the psychological aspect of a breakdown is an important factor which has to be considered. For example, a serious breakdown occurs and there is a momentary extinction, or at any rate a diminution of the lights. There is probably a blowing-off of steam, and this, combined with the uncertainty as to what has actually happened, has a numbing effect on the operators. Several seconds must pass before anyone can get going again, and then, the generating station being a large one covering a considerable area, even when a man's mind is made up it takes him some time to get to the particular switch or valve which has to be operated. These operations cannot be rehearsed, and a fault occurs without any warning. I think that, taking all these things into consideration, it will be agreed that 60 seconds is too short a time to effect the alterations necessary to start these particular auxiliaries up again. If the authors consider that Type (*b*) should not be shut down for more than 60 seconds, I think that Types (*b*) and (*a*) should be amalgamated, i.e. the auxiliaries in (*b*) should be put under (*a*). Type (*c*) deals with those auxiliaries which must not be allowed to stop for more than 5 minutes, and I think that what the authors suggest there for the particular auxiliaries concerned could be carried out within that time. My only remark with regard to (*d*) is that a 12 hours' accumulation of ash in some stations might completely choke the grates, etc. I agree that rotary converters are not desirable in a generating station. It is acknowledged, of course, that induction motors are the most reliable, as they remain in circuit when a breakdown occurs, but I do not think it is altogether realized how good are synchronous motor-generators. I have known many occasions when they have kept in step, in spite of the fluctuations, and have still given their load. The synchronous motor-generator also has the advantage of being able to convert alternating into direct current, or vice versa, and I think, therefore, that there is something to be said for the synchronous as compared with the induction motor, which latter cannot, of course, be reversed. Then there is the question of batteries; I was rather interested to hear that the authors had modified their opinion somewhat on this question, and also to hear Mr. Woodhouse's remarks as to the reliability of d.c. motors. I am entirely in agreement with him there; I think it is a mistake to economize too much on the battery. One has in it a source of power which is immediately available, and, if one can utilize it at a very high discharge rate, a great deal can be done with it and thus give time for other sources of supply to be started up.

**Mr. J. S. Highfield:** The paper raises a subject of first-class importance, particularly to the operating station engineer. The authors quite rightly point out that the absolute continuity of supply provided by the various auxiliary apparatus in a big power station is of the first importance. It is a matter not only of maintaining the supply, but also of saving the plant from very heavy damage; moreover, if the auxiliary plant is used in the right way it will lead to considerable economies. I do not altogether agree with the authors that their Schemes 1, 6 and 7 are of equal merit; I think that Scheme No. 7 is infinitely preferable to the other two, for the reason that it is essential that feed-pumps, circulating pumps and certain other apparatus should be run quite independently of the main plant; at any rate, a certain proportion should be run independently of it. That can be done in only two ways. Either one must have separately-driven feed-pumps and circulating pumps driven by separate steam plant, or else these auxiliaries must be supplied from an auxiliary turbine which runs quite independently of the main station supplies. I prefer the latter method, and the authors have given many reasons why it is to be preferred. First of all, I think that feed-pumps may all be steam-driven with advantage. In some cases, perhaps, too much steam is provided and it goes to waste, but as a rule a large station can absorb, in feed-heating, the whole of the steam from the feed-pumps, and in that case I think that it avoids complication if the whole of the feed-pumps are steam-driven. With regard to the circulating pumps, I think that at any rate a supply of circulating water sufficient for safety should be kept running at all times, and I prefer those pumps to be run from an independent, steam-driven auxiliary generator—whether a.c. or d.c. does not matter for the moment—the relative advantages of those two sorts of motors are well known—but that the supply should be taken from a steam-driven auxiliary generator is, I think, essential. The other auxiliary plant can, in perfect safety, be run from the main busbar. Consequently, to get a completely independent supply, I think that Scheme 7 is very much better than Scheme 1 or Scheme 6. Scheme 6 depends for its reliability and its independence of the main busbar supply entirely on the use of a battery. That is a very useful appliance so long as it is fully charged, but when serious accidents occur in a power station, unless it is of enormous size the battery is very likely to become discharged and therefore useless. I think, however, that a battery is essential with a large plant to maintain a certain amount of light. Having dealt so far entirely with questions of reliability, the next thing is to attain the best economy. A great deal could, I think, be done by using the heat from the auxiliary turbine in Scheme 7 for feed-heating purposes. The problem of using the waste heat is quite a difficult one, because the proportion of waste heat to the total steam used in the main plant varies according to the total load on the plant. It varies from time to time, and consequently great care must be taken in design to see that the amount of waste steam can be varied sufficiently to meet the requirements of the total plant for feed-heating purposes. That can be done by throwing part of the load from the main plant on to the auxiliary plant from time to time, by varying the efficiency of the auxiliary plant by running with a higher or lower vacuum, and also by having a sufficient storage of water, if possible, so that heat can be accumulated or lost with varying load.

**Mr. L. M. Jockel:** At the commencement of the paper, under the heading "Different Types of Auxiliaries," the authors emphasize the necessity for avoiding, at all costs, loss of vacuum, but one can hardly imagine a large turbo-alternator set, say of 10 000 or 15 000 kW upwards, being run to atmosphere for more than about two minutes. If any operating engineers have tried it with modern water-tube boilers, I think they will agree that the results are rather disastrous, particularly on the steam side. It is generally impossible to run at all; a complete collapse results. On the next page, under the same heading, the authors divide auxiliaries into four types, according to the length of time for which they may be allowed to stop. If the air-extraction pump is included under (*a*), I think the water-extraction pump should also be brought under the same heading. It is quite possible to run on full load for a considerable number of minutes without the air-extraction apparatus; to do so for 5 minutes is quite possible and easy with a good modern plant. I have seen it done for 10 minutes, and, if the plant is in good order, there is not a very appreciable drop in vacuum unless there are some of the old-type auxiliaries fitted, which, on their collapse, may break the condenser to atmosphere. Nowadays, of course, they are not installed, and therefore I think that the air-extraction plant should certainly be altered in its grouping. Then, under (*c*), which deals with auxiliaries that can be allowed to stop for not more than 5 minutes, the question of independent ventilating fans (I presume fans for alternators) is raised. In many cases, independent ventilating fans can be shut down for long periods, provided, of course, that one is cognizant of the loading of the alternator and reduces it to the necessary amount, which depends chiefly on the design of the machine. It may be possible to run for hours with $\frac{3}{4}$ load or less. With modern closed-circuit air systems the question is much more serious, and several stations are now contemplating putting in a stand-by cooling air supply for the closed-circuit system. Again, under the same heading, dealing with Type (*a*) the authors say: "That a loss of vacuum will at once follow a stoppage of the air extraction is a self-evident fact." I disagree with that. The air-extraction plant can be stopped, but the vacuum will not immediately follow it. For example, if the air-extraction plant stops it is possible to get another turbo set started and actually on the busbars before switching out the machine on which the air-extraction plant has failed. I have helped to do this on more than one occasion. I am very glad to see that the authors emphasize the importance of duplicate auxiliaries for the condensers. That is a most important point, particularly with the larger units. I am also glad to notice that they emphasize the importance of the feed-pumps, and state that one of the most suitable schemes is to have one motor-driven rotary pump and one steam-driven rotary pump for each group of boilers. That is standard practice now, I take it. Next, in considering the different types of auxiliary supply available, I am pleased to note that the authors are not prepared to advocate direct steam-driving. That method was very fashionable some years ago, and at first sight it appears to be an extremely economical and reliable proposition. Although I hold no brief for the direct steam-drive, I think that the value of the paper would have been enhanced, and the authors' case against the direct steam-drive strengthened, if they had given a brief comparative statement or some data for an alternative scheme on those lines, say for driving a proportion of the alternators. There is a certain amount of fascination in the thermodynamic aspect of auxiliaries. The first consideration, of course, must always be reliability; economy must come second. With regard to steam-driven auxiliaries, I have actually known cases where it was necessary, with direct-driven steam auxiliaries, in order to avoid either a complete shut-down or low frequency for a very long period on the supplies, to shut the set down altogether, having previously started a set with electrically-driven auxiliaries in order to prevent total collapse. The thermodynamic aspect is admittedly fascinating, but now that turbo-alternator engineers are resorting to "bleeding off" the fashion becomes more ethereal, as bleeding-off is a highly economical and reliable proposition. It is, I think, very significant that both at the Dalmarnock and the Gennevilliers capital stations electrically-driven auxiliaries have been adopted. In the case of the Gennevilliers plant a certain number of important auxiliaries are arranged for direct driving with steam turbines, notwithstanding the fact that they are there for emergency purposes or experimental heat-balance tests on the station. I think that the authors have hardly done justice to system (B), namely, electric drive from main alternators via high-tension busbars. That system is very largely used, and, although it has certain drawbacks, these can be overcome to some extent in a carefully designed scheme, particularly if a proportion of the auxiliary motors are driven by direct current, and the batteries are used. If one employs rotary converters in connection with that scheme, they may reverse under certain conditions, and one needs to transfer such auxiliaries as can be changed to another supply. Asynchronous motor-generators are far more stable. Some synchronous motor-generators will change over excellently from motoring to generating without any attention whatever, but there are some which will not do so successfully, and therefore a complication is introduced at once, and, using the synchronous motor-generator for linking up, the gain in efficiency will be very small indeed. In regard to the question of d.c. versus a.c. motors, I think that the upkeep and attention needed with the former has been overstressed. Trouble is experienced, but very often it can be traced either to the motors being too small for their work or to the fact that severe competition, with the consequent necessity for cutting the price, has made the work inferior. Again, they may have complicated windings on the fields, which render the motors more unstable. I think it is quite possible to sacrifice efficiency very appreciably by adhering too closely to the greater simplicity offered by induction motors. As to the control of centrifugal pumps and fans, etc., the d.c. motor appears to be the most convenient and economical method for this purpose, as the valve and damper control mentioned by the authors does not give exactly efficient regulation. The heat generated is proportional to the square of the speed, whilst the power required is proportional to the cube of the speed. I am not convinced that type (E), the auxiliary house-turbine system, is, to quote the authors, "undoubtedly the most popular system of auxiliary electric supply in this country" at present. In America the idea has been carried to what I might call the "hair-splitting" stage, and the results which have been published do not convince one that the heat balance is so very greatly superior, or that the thermodynamic conditions can beat the best British practice. In regard to scheme (F), I should like to ask the authors if they have considered the effect of a 10 per cent or 15 per cent over-speed on the main unit, i.e. the auxiliary unit on the shaft of the main turbine, and also the effect of automatic protective gear operating on the plant.

**Mr. W. E. Highfield:** Three of the schemes given in the schedule utilize a generator direct-driven from the shaft of the main set, and it is in connection with the design of that machine that I should like to make a few remarks. The suggestion is that there should be a 300 kW set for a 3 000 r.p.m. machine, and that for 1 500 r.p.m. the set should be of 450 kW or thereabouts. First consider the d.c. machine. It can be designed to give its output quite as well as a lower-speed machine, but it must be remembered that the design will be of a very special type. It will have compensated windings; it will have interpoles; it will have a shrink-ring commutator with a surface speed of 8 000 to 10 000 ft. per min. I do not mean that the machine will not run, and run continuously, but it requires constant attention, perfect trueness of the commutator and constant setting of the brushes to maintain consistency of running. Such a machine does not compare favourably with a similar machine at 1 000 or 750 r.p.m., which will still run whether these things are attended to or not. Another thing that I think is very germane to the adoption of such a system is that the shaft will run through the critical speed, which will probably—in fact, almost certainly—be different from that of the main alternator. Consequently one will almost certainly have to put in another flexible coupling, and the machine itself will add 6 ft. to the length of the original set. Even in the case of an alternator there will still be the same shaft problem to deal with, i.e. the machine will run through a critical speed, and probably another flexible coupling and two bearings will have to be introduced. I think that is a very great drawback to the three particular schemes (1), (3) and (4). Under the heading of "Different Types of Auxiliaries," dealing with Type (*b*), the authors refer to a group of boilers fed by two feed-pumps, one steam-driven and one electrically driven. That system will be all right when the whole group of boilers is working, but what happens when only a few of the boilers are running? It seems to me the system will be uncontrollable when half or less of the boilers are at work, because the pumps must be run at full speed to get the right pressure, and the only control available is that provided by the check valves.

**Mr. J. R. Cowie:** Dealing with the different types of auxiliaries, the authors include under (*d*) those which may stop for a period of up to about 12 hours, including the coal and ash conveyers. I am not at all sure that a little more attention is not needed for these. The authors put the bunker capacity at 12 hours. It is quite common to have one conveyer for storage coal coming into the boiler house, another from the railway siding lines for direct feed, and only one conveyer across the top of the bunkers going to the boilers themselves. A second conveyer here would mean the saving of extra height on the whole of the boiler house and permit of a bunker with a capacity of less than 12 hours. With regard to steam drive for circulating water pumps, quite a good practice is to have 60 per cent of the circulating water steam-driven and 60 per cent electrically driven. In this case a good many of the authors' contentions with regard to the special generators for auxiliary supply do not apply. I am in agreement with the authors in regard to extraction pumps, although there is a good deal to be said for a steam-nozzle stand-by, provided that the steam supply for these nozzles is taken from the right place. The next thing is the question of direct steam drive, and the authors refer to the house turbine sets at Dalmarnock as being available for the condenser auxiliaries. This is not quite correct, because these sets are also available for the whole of the auxiliary supply to the auxiliaries. The turbines themselves, i.e. the house turbines, can be adequately protected by discriminative apparatus, and the only thing necessary to protect them from trying to take the whole station load in time of trouble is adequate overload with a slight, definite time limit. To take the auxiliary supply by means of a step-down transformer from the alternator terminals was common some years ago, and has been, in another form, used in sets Nos. 3, 4 and 5 at Dalmarnock, as stated by the authors; but it should be noted that an auxiliary supply is necessary to start up the condenser units when the turbine is going on load, and this supply comes from the main supply board to the whole of the auxiliaries. The change-over from the auxiliary supply to the step-down transformer is taken through a set of quick-change-over switches. That arrangement is in force in many parts of the country and is running satisfactorily. In regard to the boiler house, it is assumed that a forced draught is used. To some extent the sort of draught that is used influences the question of whether a.c. or d.c. auxiliaries should be employed. I am in favour of Scheme 7, but I should prefer it to be alternating current. I do not care for most of the schemes, for the simple reason that while they give the transfer from each section they do it by means of expensive transfer bars, and interposed in these transfer bars is a section switch of a different capacity from the other main switches. There is a danger that this switch may be closed with the sections not yet synchronized, because it is usual to run a super-station with the busbars and the networks sectioned at peak load. I agree with the authors that in emergency one has to borrow between sections, but I maintain that the low-tension and not the high-tension side is the place for this transference, the main high-tension sections having first been paralleled through their oil-switch section switches. In Fig. 7 a multiple busbar is shown on the secondary side. I should prefer a single busbar arrangement with a section switch in between, each bar being divided up so as to cover separate sections and separate sources of supply. In the paper 3 000 volts is given as the supply pressure for larger auxiliaries, but it is quite common to find small motors driven at 3 000 volts, and I have in mind one large station, now under construction, where high-tension power is used for the large auxiliaries and low-tension power for the small auxiliaries, while direct current is used for such of them as need wide speed variations; but there is a way of getting speed variation where needed (depending on the type of auxiliary) by means of slight speed variation of 3 to 5 per cent on the rotor of an a.c. motor and, in the case of the fans, in addition by means of dampers on the draught side. The paper raises the most difficult problems and had it gone further and stated how the power was to be taken in each case to the individual places and thence distributed it would have been even more useful. Again, if it had given the relative capital expenditure in each case this would have been most instructive, for the worst job of all is to work out the cable system for a really big station. With regard to the question of alternating current versus direct current, the only place where the latter need be considered is on the fans and on the station lighting in the case of a shut-down. In the case of the fans this work can be done by means of alternating current and therefore I contend that the only place for d.c. work is (1) for station lighting, and (2) for switchgear solenoids. The authors say that the auxiliary switchboards should be close to the control engineer, but he is generally separated by a considerable distance from the power station, and the senior and junior shift engineers are in the engine room and boiler house. It is in these places that the heaviest loads have to be dealt with, and I think, therefore, that the place for the auxiliary switchboards is at the heaviest load centre—the boiler house.

**Messrs. L. Breach** and **H. Midgley** (*in reply*): In reply to Mr. Woodhouse, we would suggest that it is rather an exaggeration to say that an a.c. system entails rigidity of connection. After all, with the sections suitably divided by reactances, it is possible to limit to some degree the effect on the whole system of a local disturbance, although we agree that it would be advantageous if this limitation could be made still greater. The criticisms of the d.c. motor were not given with a view to ruling it out altogether but rather to consider judicially the relative merits of alternating and direct current before expressing any opinion. We should like, however, to add that in our experience there have been several cases of d.c. station auxiliary motors flashing over at times of trouble, and this is a serious disadvantage from which the a.c. type is free.

The bad effects of a shut-down hardly need to be enlarged upon, for most operating engineers know only too well what it means, and we are therefore inclined to agree with Mr. Brazil's suggestion that all the station lights should be fed from the battery. Regarding the classification of the boiler feed-pumps and the control circuits, we agree that the latter should be transferred to Type (*a*), i.e. to the group of auxiliaries which must on no account stop. In the case of the boiler feed-pumps, whilst there is much in favour of their transference also, it is considered that on the whole this is scarcely necessary as long as provision is made for an alternative pump being available for use within the 60 seconds allowed for Type (*b*). The period of 12 hours for Type (*d*) was given as a round figure, and of course, if a shut-down of this length were not permissible for any of the auxiliaries in this class, suitable provision would have to be made so that the supply could be restored in a shorter time. Whilst, in certain cases, synchronous motor-generators have advantages, we consider that unless reversibility is required, induction motors are more satisfactory for auxiliary work, owing to their not falling out of step and to the ease with which they can be put on load or changed over from one supply to another. We have not modified our opinions on the general question of the use of batteries, but have slightly altered the remarks which we made in the advance copies of the paper distributed at the meeting in regard to the question of voltage regulation.

With reference to Mr. J. S. Highfield's remarks, it is interesting to note that the cost of a battery for the station considered in the paper, capable of carrying the load of half the station auxiliaries for 1 hour, would be about £0·3 per kW, or, assuming the station to cost £25 per kW, 1·2 per cent of the total station cost. It is suggested that this sum would be well spent for the security obtained.

The discussions have shown that there is very great difference of opinion as to the relative merits of steam versus electric drive of boiler feed-pumps, and we feel that the best answer to those who object to electric drive for this auxiliary is to refer them to the speakers who are in favour of it.

We agree with Mr. Highfield that the use for feed-heating of the waste heat from an auxiliary turbine is very economical, but such an arrangement necessitates some device for varying the load on the auxiliary turbine to maintain a constant feed temperature, and we consider that it is advantageous to avoid as far as possible such complications in the auxiliary supply.

Regarding Mr. Jockel's statement that it is possible to run with the air-extraction apparatus out of commission for a period of 10 minutes, we suggest that this is only true if the pump is of such a design that it will draw out some of the air together with the water. With a modern turbine and condenser and a water-extraction pump of the rotary type it is not possible on full load to shut down the air-extraction plant for more than a few seconds. Mr. Jockel's statement that stand-by air-cooling arrangements are being adopted for turbo-alternators fitted with modern closed-circuit systems is noted with interest. There may be "a certain amount of fascination in the thermodynamic aspect of auxiliaries," but we are very strongly of the opinion that this side of the subject has been rather overdone, and that reliability and simplicity are of such importance that reliability should never be sacrificed to economy, and simplicity only if a very considerable increase of economy results. When synchronous motor-generator sets intended for reversibility are being ordered it would be advisable that the specification should include a provision that they are to be capable of running from either the a.c. or the d.c. side, and of changing from one to the other without falling out of step.

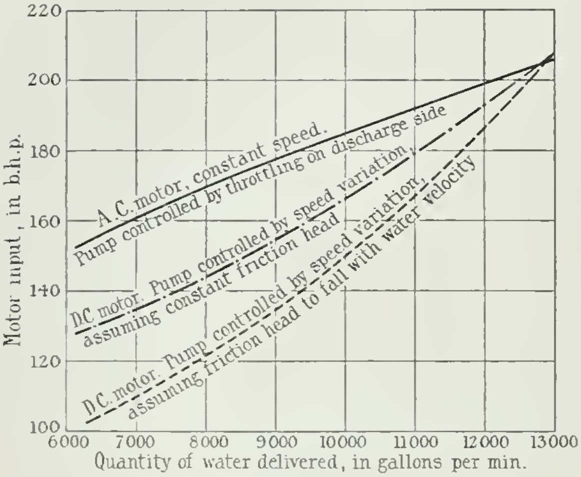


Fig. A.

Since reading the paper we have obtained from Messrs. Mather and Platt figures as to the relative efficiencies of d.c. and a.c. motors driving a centrifugal pump, the control in the latter case being carried out by the use of valves. These are shown in Fig. A.

An overspeed of even 10 per cent of the main unit would only occur in case of emergency, and, as it would cause the overspeed trip to operate, the shutting down of the auxiliaries fed from the special generator on the main shaft due to operation of the protective gear would not be a serious complication.

We note with interest Mr. W. E. Highfield's remarks on the design of a special auxiliary generator on the main shaft, but we are rather at a loss to understand his difficulty regarding the boiler feed-pumps, as, with centrifugal pumps, constant-speed running with regulation at the check valves is a method adopted in several stations with satisfaction, and is in fact actually recommended by one well-known maker.

In reply to Mr. Cowie, we feel that the consideration of the capacity of coal bunkers is beyond the scope of the paper, but that arrangements for the supply of power to the auxiliaries would, of course, be modified as found necessary to suit the individual conditions of any of the auxiliaries. Regarding the switches between the sections of what Mr. Cowie calls "transfer busbars," these are only for use during cleaning, and further, it is pointed out on page 834 that the arrangement shown for the main busbars is purely diagrammatic and that consequently the sub-busbar would depend to a considerable extent upon the arrangement of the main busbars. These considerations make it difficult to discuss very satisfactorily the high-tension arrangements for the auxiliary supply, but speaking on general principles we consider that the transfer of auxiliary supplies should be carried out on the high-tension side rather than the low-tension side.

The question of giving capital costs of the various schemes was considered, but as any such figures would only apply to one individual case, and as the danger of drawing general conclusions from a particular case is very great, it was decided not to include them, whilst considerations of space prevented the inclusion of any discussion of the cables to the auxiliaries.

In view of the remarks of Mr. Cowie regarding the location of the auxiliary switchboards, we consider that it might be advantageous to amplify what is said in the paper in regard to this point. The switches controlling the main feeders to the boiler-house and engine-room auxiliaries should be controlled from a board close to the main control board, so that the operator of this auxiliary board may receive leading instructions from the main operator. The latter, rather than anyone stationed in the boiler house, should be in a position to decide what sources of supply are available for the different groups of auxiliaries. The switchboards controlling the individual motors and their feeders should of course be as close as convenient to the groups of motors which they feed.

## Mersey and North Wales (Liverpool) Centre, at Liverpool, 16 April, 1923.

**Mr. P. J. Robinson :** It would appear that the authors have largely confined their schemes to work in conjunction with a riverside station. At the moment I am personally most interested in the cooling-tower proposition and, as many lay-outs are not applicable to both riverside and cooling-tower schemes, it is not easy to deal with much of the subject matter. However, before offering suggestions of an alternative scheme to the one produced, there are one or two portions of the paper which I think deserve attention. I agree with the authors that it is essential that money should not be spared to ensure against possible breakdown in the auxiliaries. On page 831, paragraph (B), it is suggested that the auxiliary voltage should be in the neighbourhood of 3 000 ; at any rate a statement is made that it merits careful consideration. The authors appear to have dealt so effectively with the disadvantages of this voltage in the following paragraph that it is hardly necessary to criticize the first statement. On page 832, paragraph (F), the authors refer to a recent proposal of placing a d.c. or a.c. generator on the shaft of the main turbine. It would be interesting to know whence this proposal emanated. Personally, I agree that it has much to commend it ; the only question is whether an additional generator on the shaft is practical. There is also the question of building a d.c. generator which would be satisfactory at the size and speed. It would, of course, considerably increase the overall length of the machine, and the exciter for the main generator would have to be taken carefully into consideration as this should be so connected that in the event of failure on the d.c. generator this portion could be disconnected without interfering with the main set. The scheme of the auxiliaries being driven with a secondary generator on the shaft would appear, however, to have the advantage of the most economical steam consumption, and would come under the attention of the same driver as the main set. In putting forward the secondary generator I cannot see any advantage in making this alternating-current, as if the turbine slows down from any cause, either low steam pressure or excessive overload, the auxiliary plant will also slow down and set up a vicious circle. I regret that the authors consider as being outside the scope of the paper what has been up to now the most reliable piece of machinery yet produced for generating work. I refer to ejectors, mentioned in col. 2, page 833. I hardly think that these should be left out of consideration, and apparently the authors have to some extent changed their minds as on page 839, col. 2, they invite opinions as to the provision of an air ejector. I would point out that a steam air-extractor is unaffected by any trouble likely to occur in a station, such as low steam, and appears from a generating point of view to be one of the few pieces of plant that can be relied on under almost any conditions however bad. It is also very efficient when properly installed. A statement is made on page 833, col. 2, that the use of two circulating, two air and two extraction pumps is essential. It may be desirable, but is not necessarily essential, if I understand that these pumps are to be installed in a stand-by sense. The general belief amongst users of feed-pumps seems to be that the electrically-driven feed-pump is not as satisfactory in practice as the turbo-driven feed-pump, and personally I should prefer two steam-driven turbo pumps to one steam and one electrical. With regard to the changing over of a.c. supplies, page 834, I do not think that any useful purpose would be served by a time-lag of, say, 30 seconds, because in the event of one section of the station failing badly it is possible that the trouble might be lengthened by this time-lag, owing to the section being paralleled through the auxiliary supply. On page 831 the authors suggest using valves on circulating pumps for the regulation of the flow in what is a necessity, a non-variable-speed a.c. motor-driven pump. This in practice, however, is unsatisfactory, as if the valve is placed on the suction side of the pump erosion is set up when one starts to throttle, and if on the discharge side of the pump the head is increased and erosion is again set up through the pump being run under conditions for which it is not designed. With regard to the general drive of the auxiliaries (and this applies probably more to cooling power stations than a riverside station), it seems highly undesirable that they should be driven entirely by alternating current, as any diminution in the pressure with a corresponding drop in speed immediately sets up a vicious circle through the slowing down of the auxiliaries. In the general schemes 1 to 6, I notice that the authors put forward a ring-connected switchboard on the high-tension side of the auxiliary supply. I consider this to be an unnecessary complication with few or no advantages. It is neither simple nor foolproof, to use the authors' own term, and there is considerable danger from the supply in case of trouble being accidentally paralleled on the auxiliary h.t. supply. A preferable method in my opinion would be to take the feed for the auxiliary transformers from between two link switches on the h.t. bars, putting two link switches together in the place of one, or by using throw-over isolating switches to enable this to be done. The different boards could then be cut off for examination and cleaning because one would be in a position to put the transformer on either of the two sections of the boards. It is possible also, by means of throw-over switches on the low-tension board, to place any section of the a.c. distribution system on to any bank of transformers, thereby avoiding all chance paralleling either on the high- or low-tension side. Without criticizing in detail any of the seven schemes put forward, I would suggest that the authors consider the following method of dealing with the auxiliaries of a main power station :—

*Feed pumps.*—Steam-driven turbo feed-pumps in duplicate, exhausting to feed water.

*Stoker motors.*—One a.c. and one d.c. on each section.

*Fans.*—These might be half a.c. and half d.c., or all a.c., with duplicate feed in the case of all a.c., if possible, from two sources.

*Air extraction.*—By means of three or four steam extractors of 50 or 40 per cent capacity, each to do its full rating on 60 per cent steam pressure.

*Water extraction.*—One d.c. and one a.c., each full capacity. Circulating, two pumps 60 per cent a.c., 60 per cent d.c. This d.c. pump could be run at, say, 40 per cent capacity, and be capable of being worked for short periods 25 per cent overload or 75 per cent of the full capacity if required.

The direct current to be supplied from main-shaft d.c. generator if found practicable by the designers, or if not practicable each turbo-alternator to have its own motor-generator or rotary converter with the necessary stand-by for these converters. The alternating current to come either from the h.t. bars through transformers or from special tappings on the h.t. main transformer when the switching is done on the h.t. transmission side. A battery to be provided of a capacity to run one unit complete for, say, one hour. The station lighting to be half alternating and half direct current.

**Mr. J. Hamilton :** The authors say that their recommendations are based on the principle that no expense should be spared to secure a simple and reliable system of station auxiliaries, and they further express the opinion that the question of cost should only be considered when absolute reliability has been assured. I do not know of any system for which the claim of absolute reliability might be substantiated, and the nearest approach to this condition is reached, I think, when a stand-by battery is installed capable of supplying (for a period of, say, one hour) the total power required by the auxiliaries. After expressing these opinions, I should have expected the authors to put forward such a scheme, yet they comment on the expense of installing a battery of a size to ensure reliability in their Scheme 6 (" Effect of a fault with two or more sets on load "), and one is led to ask them if they do not think that their opinions as expressed require to be either qualified or modified, or both. It will be generally agreed that all reasonable care should be exercised to ensure continuity of supply, but to say that this should be striven for regardless of expense is placing it upon too high a plane. Under " Direct steam drive " mention is made of the boiler feed-pumps, and I should like to know the authors' reason for allocating, later on in the paper, the main duty to electrically driven pumps and keeping as stand-by one of the most reliable of station auxiliaries, the turbine-driven feed-pump, which has valuable regulating characteristics. I agree with Mr. Robinson that the steam-operated air ejector falls within the scope of the paper and, in view of its reliable features, especially on fault conditions, I am surprised that the authors have not included it under " Direct steam drive." In discussing the relative advantages of a.c. and d.c. drives the question of speed variation is raised, and I agree that on the bulk of the auxiliaries under consideration this point can be looked after in other ways, yet in one connection it is worth consideration, viz. on chain-grate stoker drives. It is true that a speed variation on the grates is provided by the gears, but there are times when it may be desirable to accelerate the speed beyond the range usually supplied. The use of special house sets entails additional attendants who would be employed practically to ensure continuity of supply to auxiliaries, and I notice that the authors claim that house sets exhausting to their own condensers would be an efficient arrangement. It would be of interest if they could give any data concerning this point, and would say whether (in view of their statement that the house set should be dissociated from the duty of feed heating) it has been considered from the point of view of heat balance. It would also be interesting to have the authors' opinions on the most reliable source of supply to the house-set auxiliaries and whether this should be in duplicate. The use of a special generator on the main set is attractive from the operating point of view, and this largely rests with designers and manufacturers to decide. In considering the arrangement of condenser auxiliaries, the authors show a scheme in Fig. 8, but I cannot follow their statement that it is essential to run the turbines in pairs. It appears to me that on this scheme it is only possible to have duplication of supply on one turbine, and to get this it would be necessary to fit two additional valves, whilst to fit pumps of twice the necessary output and run one on half load would lead, I should think, to erosion troubles. In the consideration of individual schemes, if it is possible to have a special generator in Scheme 1, it would supply the d.c. auxiliary power at the minimum steam cost, and along with this one would have standing charges on a probably increased capital cost over, say, the motor-generator sets for a practically similar arrangement in Scheme 6. The relation of these charges to the increased cost of power from the motor-generator sets would, if the authors could supply it, be an interesting figure. Scheme 2, as the authors point out, does not ensure a duplicate supply when one set is running alone, and this would probably hold good for a considerable portion of the day's running, unless the load factor is high. The special house set and push-button to rectify this drawback does not appeal to me, and I should not feel happy to think that as a last resource I was dependent on such an arrangement. The possibility of requiring in quite probable circumstances to start up on atmosphere in Scheme 3 is a feature to be avoided if at all possible, and again this scheme depends on suitable auxiliary alternators being available. The authors state that Scheme 4 should be avoided, and I should not have disagreed with them had they coupled to this Scheme 5. In both of these schemes the highly desirable feature of simplicity is lacking. Scheme 6 appears to me to contain the best features and to be preferable to Scheme 7, provided the battery is of a sufficient capacity to carry the d.c. auxiliaries for one hour. This scheme would be cheaper than Scheme 7 in capital cost and in operating cost and, I think, quite as reliable.

**Mr. A. E. Malpas :** The strength of a chain depends upon its weakest link ; therefore, in order to keep any plant, whatever its nature, running continuously, it is necessary that all the important links in the chain should be in duplicate. The question of size of installation will decide to some extent what items should be regarded as separate links. For instance, taking the case of the circulating pumps mentioned under section (*a*) on page 830, in the case of the smaller-sized units it is more usual perhaps to regard the circulating pumps, air pumps and lift pumps as being part of the main unit, and, in the event of any accident happening to any one of the separate items, to shut down that unit as a whole and start up a spare set. In this case, therefore, it is not usually considered necessary to duplicate the separate items of the unit. With larger units of, say, 10 000 kW capacity, it would no doubt be better to duplicate even the separate auxiliaries of that unit, as by so doing the station could work with a smaller number of complete large units, so tending towards smaller capital expenditure on the station. I have in mind an installation of three 1 000-kW turbo-generators of reaction type installed during the war for the purpose of the manufacture by an electrolytic process of a high explosive for war purposes. In this case each unit had its own auxiliaries not in duplicate, so that in the event of any accident to any part the spare set had to be put on load in place of the defective unit. The plant was required to run at full load, day and night, continuously in order to maintain the maximum supply of high explosives from the plant. In the event of an accident it was found impossible to work the crippled set to atmosphere on account of the very greatly increased steam consumption lowering the boiler pressure and so interfering with the smooth running of the working units. With reference to the remark made at the top of page 830 as to the rise of temperature on blades at the low-pressure end when working to atmosphere, the temperature at 28 inches vacuum is 40° C. and at atmospheric pressure 100° C., but I do not remember ever having seen any figure given as to the increase in temperature of the blades due to windage friction. It would be interesting to know whether any figure has been obtained for such rise of temperature. The importance of continuous running cannot be over-emphasized. A case in my own experience occurred in Madrid where we were supplying current to one of the principal railway stations from a large installation driven by gas engines. A shut-down occurred about 11 p.m. one evening just as the South express was about to leave the station, and had this shut-down occurred a few minutes later a serious accident would have happened. I quite agree with the authors, therefore, in placing the item of reliability first, as on this item the cost of production and the success or otherwise of the station very largely depend. With reference to the note on page 833 with regard to power taken by circulating pumps, it is of interest to point out that turbulent flow is obtained when the linear velocity of the water through the tubes is about 6 or 7 ft. per sec. This high velocity means a rather large expenditure of power, and the point often arises as to how far the increased economy of the main sets due to increased vacuum is paid for by the increased power taken by the circulating pumps.

**Mr. T. D. Clothier:** The question of auxiliary drive is, if I may put it that way, one of the side lines that is really the essence of the contract in power station work. It is only necessary to have a superficial knowledge of power station work to know that in any ordinary well-conducted undertaking the units generated compared with the units sold are something of the order of 100 to 80, that is to say, 20 per cent is generated and not sold. The kind of plant as regards main generating units, both steam-raising and prime-mover, that can be put in small as contrasted with large stations, compares quite well in efficiency as far as these are concerned. Large power stations, on the other hand, have to carry what the others do not, namely a heavy and sometimes inordinate expenditure on switchgear and mains to transmit the power generated to positions where it can be sold. It may be a Scottish caution, but I seemed to read a note that I did not like running through the paper, and that is the question of reliability. I think that all my life I have been trying to satisfy users that the power supply of electricity is more continuous if taken from a power station than if they make it themselves; the authors indicate a lamentable lack of confidence in the reliability of the supply at their own busbars. This surely should be beyond reproach. As to the method in which auxiliaries should be driven there again is a similar problem with which the consumers have to deal. It is well known that when steam that can be considered as surplus is available, it is generally advisable to use it for auxiliary purposes; the question to consider is how far the heat of the exhaust steam or the reduction of pressure in high-pressure steam can be regarded as surplus. The use of steam in this form does not absorb any portion of the generating plant. I would repeat, however, that I do regret the feeling of insecurity which the authors seem to have regarding their own busbars.

**Mr. T. E. Houghton:** There is only one point which I wish to raise. On page 832, in the discussion as to the disposal of the exhaust steam from the house turbine, the authors conclude that feed-heating should be accomplished by bleeding the main turbine, and not by exhaust steam from the house sets, which in consequence should be condensing turbines. Whilst I agree with the contention as far as feed-heating is concerned, I think there is another proposition worthy of consideration, namely, the installation of a pass-out turbine for house-service work, the pass-out steam being utilized in a feed-water evaporator. By this means a supply of pure feed water would be available at a fairly high temperature. In general, the weight of make-up feed water would be approximately equal to the weight of steam taken for auxiliary purposes. With a four-effect evaporator, therefore, a turbine capable of passing out 25 per cent of steam would be required. The steam consumption of such a machine would be some 13 or 14 per cent greater than that of a condensing turbine. The feed water would therefore be obtained at the cost of the corresponding increase in coal consumption of the auxiliary turbine. Taking usual figures I find that the cost works out at about one shilling per thousand gallons of water obtained.

**Mr. J. H. Collie:** My own idea is that for some of the auxiliaries, especially boiler-feed and circulating pumps, it is desirable to use a steam drive, with stand-by of either steam or electrically-driven pumps. The two principal auxiliaries are then quite independent of the station supply. As to the difference in efficiency of steam and electricity for these auxiliaries, I do not think there is much to choose between the two. I also think, taking everything into consideration, that d.c. motors with their flexibility of speed are preferable to a.c. motors. The present d.c. interpole motors are very reliable, and if not continuously overloaded they give practically no trouble. The proposition of a stand-by battery for auxiliaries and lighting appears to me to be very desirable, and if this is provided it seems almost unnecessary to have house generating-sets. The power for driving the motors normally can be provided by rotary converters fed from the main busbars, with change-over switches to battery supply, either hand or automatically operated. As to the question of high-speed d.c. generators for auxiliaries on the main turbine shafting, I have had some experience with high-speed radial-commutator d.c. machines, which are generally satisfactory if the commutator is kept in good condition. They are rather apt to flash over in the event of heavy short-circuits, and I doubt whether manufacturers would recommend them for such important duty. It would probably be considered better practice to drive these generators by gearing.

**Mr. C. Rettie :** With reference to the question of the remote-control gear raised on page 844, I have had a good deal of experience with such gear of d.c. type in marine work, particularly on H.M. ships built and repaired during the war, and I have never had any trouble beyond an occasional adjustment of the contactors. However, I should like to ask the authors if they have had any experience with alternating-current controls and have found them as reliable as the direct-current type.

**Mr. A. Stubbs :** I should like to state what appear to me to be the underlying principles of the paper. (1) The auxiliary drive must be reliable, and under this heading we may, for convenience, include simplicity, foolproofness and attendance required. (2) The auxiliary drive must be the most economical consistent with reliability, and for convenience this heading may be taken to include first cost and running charges. The authors are hardly consistent when they state that no expense should be spared in order to secure reliability, for throughout they try to strike a balance between running costs and reliability. I believe that the authors have decided that economy can be best obtained by taking the auxiliary supply from the main turbo-alternator set, and they appear to be very reluctant to sacrifice this source of supply. It is indeed this aspect of the problem which has largely given rise to the subject matter of the paper. Whilst I agree with the authors' views, I think that the value of the paper would have been enhanced if figures had been presented showing the justification of the electrical drive as against the steam drive. The steam drive is not condemned because of pipes, valves and leakages; there is something much more difficult to deal with, viz. the low efficiency of the small unit; were this not so, I am sure that many of the other objections would be overcome. Such considerations may not be very important at the present time, but it is quite possible that they may save us from developing too far in the one direction in the future. I would ask whether the inefficiency of the small-auxiliary-turbine drive arises from the low thermodynamic efficiency or the conditions under which the turbine is required to work. It will be noticed that the conditions may be subjected to variation in accordance with the general developments in power station practice. For example, in modern power stations where feed-water temperature appears to be increasing at the expense of the economizer, and where two-stage heating to 210° F. may be adopted, the auxiliary turbine exhausting at atmospheric pressure could be incorporated in the feed-heating system to better advantage. High steam pressures are presumably unfavourable to the small turbine, but it is possible that still further developments in steam pressures (to, say, 1 200 lb./sq. in. gauge) will be in conjunction with the double-pressure station where the second pressure may be about 200 to 250 lb./sq. in. gauge, which pressures are well within the scope of the auxiliary turbine. It would appear wise, therefore, always to keep these points before us. I agree with the authors that heating steam, whether for feed-heaters or evaporators, is best provided from the main turbine. On page 829 the authors have endeavoured to give some idea of the relative importance of continuity of supply at different types of generating stations, but it is quite possible that a stand-by steam generating station for a hydro-electric system may require a continuity of supply equal to that of any other station, and I would suggest that the true comparison in a case of this kind is between running economy and low capital cost, whilst retaining the maximum degree of reliability and simplicity. A house service set supplying a.c. power continuously to half of the essential auxiliaries in the station might be instanced as good practice, and I have in mind a Japanese steam generating station designed for 100 000 kW capacity consisting of four 25 000-kW main turbo-alternator sets and two 1 000-kW house turbo-alternator condensing sets, this station to feed into a hydro-electric system of 400 000 kW capacity. Referring to page 830, I would suggest that the Type (*d*) auxiliaries will gradually merge into Type (*c*), and that bunkers and tanks within the power station are likely to be reduced in the future. Will the authors state why boiler feed-pumps have been considered to be particularly suitable for steam drive? The reasons given in the paper can, I feel, be only incidental and not the main justification. The most substantial reason in all probability refers to operation, for various operating engineers have in this discussion spoken in favour of this type of drive. The heating of the boiler-feed due to the exhaust from the turbine-driven boiler feed-pump is only sufficient to give a rise of from 15 to 25 degrees F. The use of variable-speed a.c. motors of the pole-changing type, together with the limited use of dampers and valves, might yield higher overall efficiencies with no other disadvantage than that of increased cost and an extra switching operation. Referring to the house turbine mentioned on page 832, the variation in vacuum of the main condenser due to the variation in load on the main turbine would not have such a marked effect on the output of the house turbine when exhausting to the main condenser as would be the case when the house turbine is exhausting to a higher stage of the main turbine. The following suggested arrangement of house set which has not been mentioned by the authors may be of interest. This arrangement consists of a house turbo-alternator set running light, in parallel with the main supply. The turbine when under load normally exhausts to atmosphere, but when on no load the losses of the set are supplied electrically and reduced to a minimum by connecting the casing of the house turbine to the main condenser. The air leak between main condenser and house turbine enables a vacuum to be created in the casing of the house set, and the windage losses are thus reduced to a minimum and at the same time the rotor is prevented from overheating. I believe that d.c. generators of the sizes and speeds mentioned in the paper have been manufactured, but there has been no call for them of late years. Reference is made on page 833 to a scheme adopted in America which provides an auxiliary supply from a separate d.c. generator driven by an a.c. motor and a steam turbine. I cannot conceive the danger cited by the authors, for, if the a.c. motor tries to generate, the governor of the house turbine would take care of the load, and if there were a tendency to overload the turbine the speed would merely drop until the a.c. machine ceased to generate. Referring to page 834, one of the decided objections to feed-heating with exhaust steam from auxiliary turbines is the non-automatic control of the feed temperature. Considering Schemes 1 to 7, it would have helped me considerably if the authors had stated to what extent they were relying on the high-tension switchgear protection, the sub-busbars and reactances to maintain an alternative source of supply in case of failure at a particular point of the system. Schemes 1, 4 and 5 are similar as regards the source of supply. It would not be sacrificing very much to do away with the complicated change-over switches of the latter schemes, 4 and 5, and if this were done the alternating-current schemes would have much to recommend them as far as the motor proposition is concerned. The house turbine is recommended under those conditions where the station must be started up without an external supply, and Scheme 7, modified in such a manner as to provide for alternating instead of direct current, with the house set taking half the essential auxiliaries, would present a very good arrangement without unduly decreasing the economy. The authors have made reference to large turbines exhausting to atmosphere, and on page 830 it is stated that trouble arises from the temperature of the blades at the low-pressure end of the turbine consequent upon the heat from the windage losses which may cause serious distortion and damage. Will the authors state whether this is for a light- or a full-load condition, and whether in the case of an impulse turbine the blades referred to are on the discs or the diaphragms, and, if on the latter, whether designs have not already been improved so as to take account of this condition? The real difficulty is due to the rapid change in the temperature conditions, the rate at which expansions take place between the various members of the turbine and between the different parts of the same members. The capacity for heat and the rate at which heat can be transmitted will determine the rapidity of the expansions of a certain member. The internal stresses or stresses between members may be excessive when steam conditions in the turbine are suddenly changed. The same remarks apply to the condenser casing, which is usually a massive cast-iron structure. The practice suggested by the authors of suddenly starting up the main 25 000-kW set to atmosphere appears to be very far from that recommended recently in the American Journals, viz. that the starting period for 30 000-kW sets should be 1¼ hours. The condition, however, is not nearly so severe as that referred to on page 830, where the turbine instantaneously passes over to atmosphere, for the rate of change of temperature is not likely to be so marked. It would be interesting to know how the authors propose to protect the condenser under such conditions, and whether an exhaust-steam sluice valve has been considered necessary. The electrical end of the proposition does not appear to be impossible. A similar kind of procedure has already been practised for some years in connection with the starting up of textile mills where turbo-alternator and induction-motor drive has been installed. The conditions are more severe in this instance as the starting load represents a considerable portion of the normal load, whereas in the proposition put forward the auxiliary load is only a small percentage of the main alternator output. It should be noted that the practice of starting to atmosphere does not present a particular feature of Scheme 3 excepting in so far as the auxiliary alternator may be more easily excited from an external source than the main alternator.

**Mr. O. C. Waygood:** With reference to the scheme referred to under (D), page 832, adopted by the Glasgow Corporation, I should like to suggest to the authors that in revising the paper for the *Journal* they give details relative to the working of this particular scheme. It would, I feel sure, add considerably to the various schemes outlined in the paper.

**Mr. H. Dickinson:** A paper of this sort comes at a very opportune time because the lay-out of auxiliaries is becoming more and more important and a great amount of thought is being devoted to the subject. At the present time the house turbines seem to be very much favoured but, as in other things, experience may prove that this method may be improved upon. Now the authors have reviewed this particular system and they have described very fully other methods, perhaps not all the methods that might be adopted, but they have covered the ground very extensively. On page 833 the scheme for running two turbines with two circulating pumps is not very satisfactory. If one pump breaks down, one of the turbines will have to be shut down or one pump can be utilized to supply the two condensers, which cannot be considered to be an efficient stand-by. A better arrangement might be to have three pumps so that in the event of one pump failing there would be still a pump to fulfil the full requirements of each turbine. In connection with Fig. 8, if the plant were to be used as suggested it would be very much better to have a valve between each condenser and its corresponding pump. By this means it would be possible to run either pump on to either condenser, whilst one of the condensers might be down for overhaul. Mr. Collie referred to the use of a.c. as compared with d.c. motors. It is well known that a.c. motors are very reliable and it is well known also that d.c. motors have given very great satisfaction in running, and if there is somewhat more attention required in connection with the latter on account of the brushgear, etc., the extra cost is not a serious factor if one is considering the use of a battery as a stand-by. There is no doubt at all that a good battery in a station is a very great stand-by in case of trouble, and, although it may be a costly adjunct, I believe that as time goes on this factor of security will lead to a more general use of batteries for stand-by purposes in the generating station.

**Mr. F. J. Teago**: I should like to suggest that an a.c. motor of the Schrage type has all the advantages of, and is simpler to operate than, a d.c. motor, since it requires no starter, and speed variation is obtained by simply turning the brush-shifting handle; the motor has also a smooth speed-range of 5 to 1 and can operate on unity power factor. Where it is desired to start up a dead station with auxiliaries driven by a.c. motors, is it a feasible proposition to install a Diesel alternator set to run the auxiliary plant until the station is on load?

**Messrs. L. Breach** and **H. Midgley** (*in reply*): In reply to Mr. Robinson's remarks as to the schemes put forward being confined to a riverside station, we would suggest that there is no difference in general principles between the auxiliary system of this and of a cooling-tower station, and that the problems raised in the case of one would apply equally in the case of the other. In omitting all reference to the air ejector, we by no means intended to suggest that it was not a satisfactory piece of apparatus. Taking into account the question of feed heating it is not quite so efficient as the rotary air pump, but we agree with Mr. Robinson that the simplicity and reliability given by it are so great as to outweigh considerably any slight loss of efficiency. The construction placed by Mr. Robinson upon the reference on page 834 to the changing over of a.c. supplies is not what we had in mind when writing this paragraph. The time-lag of 30 seconds was not intended to apply in cases of emergency, but rather to apply to a switch which would be used for changing over a motor or group of motors from, say, a supply fed from the main busbars to a supply fed from a special winding on the main transformer, such a change-over being carried out during the course of the normal working of the station. As these supplies should not be linked up on the low-tension side, a time-lag of the nature suggested would allow the change-over to be carried out without shutting down the motor or endangering the coupling bolts, but would ensure that once the change-over was carried out the two supplies would be disconnected. We cordially agree with Mr. Robinson that such a time-lag would be dangerous in a case of emergency, and if such a switch were installed it would be advisable to consider whether arrangements should not be made so that at times of emergency the change-over could be effected at once, and the time-lag cut out. We agree that the control of pumps by means of throttling on the suction side is highly undesirable, but the use of control valves on the discharge side is adopted to a very large extent in many stations with no trouble, and we suggest that the erosion referred to may be traced to some other source. As stated in the reply to Mr. Cowie in the London discussion, the high-tension arrangements for the auxiliaries depend to a large extent upon the arrangements of the main high-tension switchgear, but the installation and operation of link or throw-over switches on the high-tension bars, whilst very attractive in many respects, will be found to be very difficult to carry out in actual practice, due to constructional reasons. Mr. Robinson's proposed scheme for auxiliaries is practically Scheme 1 of the paper with certain minor modifications which distinctly improve it, and we should be interested to see the connections worked out in detail.

Referring to Mr. Hamilton's criticism of the use of the word "absolute," we quite agree that this is rather unwise and we have therefore altered the word "absolute" on page 831 to read "maximum."

We would suggest that the difficulty raised by Mr. Hamilton in regard to the speed of chain-grate stoker motors is, in the case of either a.c. or d.c. motors, a question of the range supplied in the gear box when first installed. We consider that in the event of a condensing house set being installed there would be no advantage in having its auxiliaries in duplicate, as a house set is usually sufficiently small for temporary atmospheric exhaust not to be a serious matter. These auxiliaries might preferably be driven by d.c. motors with a stand-by supply from a battery. Regarding the arrangements shown in Fig. 8, we agree that two additional valves on the common delivery pipe, one valve being adjacent to each condenser, would be advantageous and, if it is intended to run either pump for either condenser, essential.

In view of Mr. Hamilton's question as to the necessity of running the turbines in pairs with this arrangement, it is thought advisable to amplify the statement made in the paper as follows. Let it be assumed that one pair of pumps supplies turbo sets Nos. 1 and 2, another pair Nos. 3 and 4, another pair Nos. 5 and 6, and so on. When only two turbo sets in the station were running and it was desired to have the circulating-water supplies to these turbines in duplicate, if sets Nos. 1 and 2, or 3 and 4, or 5 and 6 were run, then the use of two circulating pumps only would give the necessary duplication. If, on the other hand, any other pair of turbines such as Nos. 1 and 3, or 1 and 4, or 2 and 3, or 2 and 5, etc., were run, it would then be necessary to run four sets of pumps to give the necessary duplicate supply of circulating water.

In reply to Mr. Malpas, since first writing the paper we have had an opportunity of studying further the question of the objections to running large turbines to atmosphere. The windage trouble referred to in the paper is not a serious factor, the objections to atmospheric running being as follows: In normal running at, say, 29 inches vacuum, the temperature of the last row of blades will be approximately 80° F. and of the condenser somewhat lower. If for any reason the vacuum is lost and the turbine goes to atmosphere, the pressure at the last stage will at once rise to above atmospheric pressure; if the atmospheric exhaust valve and piping are on the small side the rise may be to as much as 10 lb./sq. in. above atmosphere. The temperature of the exhaust steam will be of the order of 300° F. to 350° F. and the temperature of the blades of both rotor and stator will almost immediately rise to the same degree, but the rotor wheels and the stator casing, being of a more solid construction, will take some considerable time to reach the steam temperature. The result is that there is a considerable risk of uneven expansion, with consequent distortion or cracking. For a similar reason the rotor wheels may tend to loosen on the shaft. The same applies to the condenser and in this case there is a further danger that if the change-over to atmosphere has been due to the failure of the circulating water supply, and the latter is restarted when the condenser shell and tubes have to some extent warmed up, the sudden cooling may cause cracking and similar troubles. At this point it is interesting to note that there is a somewhat similar change of temperature at the first row of blading when the turbine changes from full load to no load, but in this case the masses of metal affected are so very much smaller that the possibility of danger from this cause is practically negligible.

Mr. Malpas raises the question of the increased economy of the turbine due to higher vacuum being outweighed by the increased cost of pumping, etc., and in this connection it is interesting to note that in one case which we worked out it was found that under the particular conditions 27·75 inches vacuum was more economical than 27·85 inches.

We consider the figure given by Mr. Clothier for the ratio of units generated to units sold to be scarcely typical, a more usual figure being that 85 per cent of the units generated are sold, and it should be remembered that the 15 per cent lost units are by no means all used on the works. At the very highest, even in a cooling-tower station, these units should not be more than 7 per cent, the remainder of the 15 per cent being lost in conversion, heating of cables, etc. As to "lack of confidence in the reliability of supply at their own busbars" we would point out that it is only by taking the attitude proposed in the paper that operating engineers can avoid a very lengthy shut-down if once the supply does fail, and that all the measures suggested are put forward with a view to improving the reliability of supply for power users.

We agree that there is much to commend in Mr. Houghton's suggestion of the use of a pass-out turbine for house-service work, the pass-out steam being utilized in a feed-water evaporator. It should certainly be kept in mind if a house-service turbine is installed, provided the make-up water is of such a nature as to require evaporation. In the event of a house turbine not being used, steam bled from the main turbine would be equally suitable, but to deal with this matter would be rather beyond the scope of the paper.

We would inform Mr. Rettie that we have had considerable experience of a.c. contactor gear and have found it to be as satisfactory as the d.c. type.

Mr. Stubbs is not quite correct in assuming our reasons for condemning direct steam drive to be something more than the question of pipes, valves and leakages, for even if direct steam drive were slightly more efficient than electric drive, the extra complications due to steam drive are a serious objection to its use for auxiliaries, provided the electric supply could be kept reliable. In addition, we would remind Mr. Stubbs that an electric cable is a much simpler and cheaper method of conveying power than a steam pipe. In the case of a steam station installed as stand-by to a hydro-electric system, although reliability is of great importance, we suggest that the less running a station has, the less is the chance of shutting down, and that therefore, in such a case, the auxiliary arrangements need not be as elaborate as in the case of a central steam power station. Mr. Stubbs's question as to why boiler feed-pumps are especially suitable for steam drive is best answered by referring him to those who have spoken against the use of electric motors for the driving of the boiler feed pump. We regret that limitations of space prevent the discussion of the effect of high-tension switchgear protection, sub-busbars and reactances in maintaining an alternative supply in case of failure at any particular point of the system, but we suggest that it would not be a difficult matter for this to be followed out by reference to the table on pages 836 and 837. We would refer Mr. Stubbs to the answer given to Mr. Malpas on the subject of large turbines running to atmosphere.

In reply to Mr. Waygood, we regret that it is not possible for us to give further particulars of the working of the Glasgow Corporation scheme embodying special windings on the main transformers, but we would refer him to Mr. Mitchell's contribution to the Dundee discussion.

The use of three pumps in place of two for the scheme shown in Fig. 8, as suggested by Mr. Dickinson, would undoubtedly give greater security against failure of supply and, as stated in the reply to Mr. Hamilton, two additional valves should be inserted on the common discharge pipe.

We consider that the Schrage motor mentioned by Mr. Teago is at present too much in the experimental stage to warrant its use for auxiliary work where only apparatus of the most robust and simple type should be installed; further, it is understood that so far it has not been applied to motors of more than 20 h.p. It would appear to be quite feasible to install a Diesel alternator set for starting up the auxiliaries of a "dead" station, but we prefer not to express any opinion as to the desirability of such a proceeding.

## SCOTTISH CENTRE, AT DUNDEE, 27 APRIL, 1923.

**Mr. D. H. Bishop**: There is no doubt that the principle adopted by the authors in their classification of the auxiliaries is the common-sense one, but there is room for a little difference of opinion regarding the motors to be put in each class. For instance, I should put the water-extraction pump under Type (*a*), especially if the air pumps are steam ejectors with intermediate coolers. Also, I feel that the power for the control circuits should come directly from the battery, as an interruption or undue lowering of the voltage on these circuits for even a minute might be attended with serious results. There is also much to be said for having all the feed-pumps steam-driven during times of trouble. With this exception, the fewer direct steam-driven auxiliaries the better, not only on the score of attention and repair, but also on account of the corrosion which goes on inside the casings when shut down, due to leaking stop valves. To vary the speed of a slip-ring motor by the insertion of resistance in the rotor circuit is not always quite so wasteful in total power as appears at first sight. For example, the main circulating-water pumps at Dundee are driven by three-phase induction motors, and one pump supplies two turbines; when one set is in operation, resistance is inserted across the slip-rings and the power falls from 145 to 83 kW. The reason is that the pipes are laid out on a syphonic system, and practically all the head is due to fluid friction; consequently the power decreases approximately with the cube of the speed, while the percentage of electrical loss only increases roughly with the slip. The disadvantage of driving pumps with a.c. motors connected to the main supply is that the circulating-water delivery is diminished if the speed of the main generator falls during times of trouble, and this defect is aggravated if syphonic head is depended upon, especially if the head is 20 to 25 ft., because, as the quantity of water is reduced, its temperature rises, and the vapour given off reduces the syphonic head and diminishes still further the flow of water. The syphonic action is then liable to stop very quickly. The effect would not be so marked with cooling towers, but it might be sufficiently serious. The alternative method of employing a generator on the main alternator shaft is attractive, because one feels that while the turbine is turning round there is going to be power for its auxiliaries, but it has the same disadvantage, namely, that the latter slow down with the system frequency. The motor speed could be kept up independently, to a large extent, with d.c. drive. I am glad that the authors mention that continuity of supply is considered to be highly important. When comparing the results obtained in this country with those in other countries, it is sometimes forgotten that the same continuity of service does not seem to be expected in the latter, and the standard demanded here costs a considerable amount of money and effort. The statement that in changing over a motor from one a.c. supply to another it has been found that coupling bolts are liable to be broken is rather interesting, and I take it that this applies to large motors only. It also seems very desirable to eliminate all methods requiring different supplies to be paralleled during emergency conditions because of the liability of mistakes being made at such times, and because of the serious consequences of a mistake. The authors draw attention to the fact that switchgear for auxiliaries requires careful selection. I should like to support that strongly. It is astonishing sometimes to see the kind of small motors put forward by reputable contractors to be used with large generating sets, upon which motors the continuity of supply rests; motors that would be supplied under competitive conditions to small shop-keepers. With switchgear it is just the same. Under emergency conditions the operating staff in power stations cannot be expected to handle the gear very gently, and it is no uncommon thing for small starting handles to be broken. The auxiliary motors and their switchgear ought to be treated in the same spirit as the main parts of the alternators. There is much to be said for contactor starting, because, if the supply to such motors is interrupted and switched on again, the motors start up and no time is lost with blown fuses, etc.

**Mr. R. B. Mitchell**: I think that the question as to whether electricity or steam should be used for driving auxiliaries has now been fairly well settled in favour of electric drive, for reasons which have been well stated by the authors. They except the feed pumps, which, of course, is quite right, but they say that the best method is to have a steam feed-pump and an electrically driven feed-pump, the one acting as a stand-by to the other. Perhaps the latest practice goes a step further, because of the fact that evaporators for make-up are now coming into general use, and exhaust, such as the feed pump gives, is required nearly always for the use of the evaporators; so that the auxiliary electrically driven feed-pump may eventually be replaced by another steam pump. Auxiliary plant in generating stations should, in my opinion, always be in duplicate. The air pumps have, for some time past, been duplicated, but I think that the best practice is now to duplicate the circulating pumps as well. There is a great deal to be said for the system outlined in Fig. 8, but I have seen no reference to it in the paper. It shows the use of an omnibus pipe between two generating sets, and that should work quite well in practice and perhaps save some capital outlay. Supplies to the auxiliary plant should, I think, not only be duplicated but triplicated, so that one may provide a safeguard against nearly everything. In Dalmarnock we have three means of supplying the auxiliaries: (1) House turbines, (2) special windings on the main step-up transformers, and (3) 440-volt transformers supplied directly from the main busbars of the station. I think that these are at least advisable, if not absolutely necessary. Another point which has been raised quite recently is the question of having one or two secondary voltages for driving auxiliaries. It is mentioned in the paper that a 3 000-volt supply might be installed for certain purposes. I do not think that this is advisable, especially when the main supply to auxiliaries is obtained from special windings on the step-up transformers. The only reason against it is the complication. There is another question, that of alternating versus direct current for driving auxiliaries. This received a very great deal of consideration when the Dalmarnock station was being designed, and we decided eventually to adopt alternating current throughout. There are no d.c. motors in the station. The main reasons, of course, were that the a.c. motors were very robust and reliable, and did not require so much attention and maintenance; and secondly, the provision of a d.c. supply introduced another complication, apart altogether from the supply for the battery. A battery for driving auxiliaries was considered to be out of the question because, for a station of the size of Dalmarnock, not only would a large capital expenditure be required, but also a considerable amount of space to house the battery. I quite realize that the d.c. motor has considerable advantages, particularly for fan driving, but, in spite of that, a.c. drive was adopted and I have no reason to regret it. An a.c. commutator motor having a fairly wide speed regulation is perhaps to be hoped for in the early future. Its cost, as compared with that of an ordinary induction motor, is great, but that should be remedied before long. Coming again to the main subject of the paper, i.e. the types of drive to be selected for auxiliaries in a power station, I am rather disappointed to see that the authors have placed the method used at Dalmarnock, i.e. Scheme 5, in the second grade. I do not realize why that should be so. Perhaps Scheme 5 does not contain the whole, but certainly it contains the main part of what we have at Dalmarnock station, which is mentioned in this connection. On Nos. 3, 4 and 5 sets, the extra windings on the step-up transformers are used for auxiliary driving. That method has been a great success, and I may add that something of the same kind is now being added to Nos. 1 and 2 sets, so that we hope before long to have a complete outfit on all of the sets, the house turbines being used only in emergency. The special windings can be used to supply the auxiliaries of any set in the station, although normally supplying their own set's auxiliaries. On the whole I think there is a great deal to be said for this method of driving auxiliaries. It is the simplest and most robust, is self-contained, and gives great satisfaction in operation. Referring to page 830, from (A) to (F), at the bottom of the second column, we have in use, as already stated, three of these methods of supply, viz. (B) Electric, from main alternators via high-tension busbars; (D) Electric, from main alternators via special windings on main transformers; and (E) Electric, from special steam-driven a.c. generator (house set). I think that with this combination we are as safe as it is possible to be. There is only one other point, and that is with regard to the use of a battery in a large power station. I think that it should be used for emergency lighting and emergency excitation only, and it is absolutely essential for these purposes. If a total shut-down occurs, as the authors have said, one must have some means of restoring the station lighting instantaneously from an absolutely safe source of supply, and only a battery can provide that at the present time. We have a battery in Dalmarnock which effects this purpose, and the lighting, which normally is a.c., can be changed over to the d.c. supply with the greatest facility. In connection with the supply to stoker motors, there ought to be two circuits provided so that, in the event of a failure in one, the supply can be obtained from the other circuit. That is just another case of the necessity for extreme duplication throughout the station.

**Mr. J. C. Christie**: I feel that we are to some extent wasting our energies in considering in detail the driving of auxiliaries before we have decided the type of station in which these auxiliaries are to be installed. Either we are going to apply our scheme to an existing station, or we are in the happy position of erecting an entirely new station. If it is an existing station, the type of generation and distribution is already known, and that goes a long way towards deciding what type of drive is most suitable for the auxiliaries. Even if the station is a new one, I think that we should first decide the system of generation and distribution most suitable to the local conditions, and then arrange the drive of the auxiliaries to suit this. For example, if the station is one where the low-tension distribution is by means of direct current, it is probable that there is a battery connected to the low-tension busbars, and it seems proper to use this battery for an alternative supply to the auxiliaries. Most station engineers will agree that no supply dependent upon running machinery can ever be quite so reliable as that derived from a storage battery. A battery has a shorter life than a generator. It deteriorates over a period of years, but it does not fail suddenly, and this makes it very suitable as a source of supply for the auxiliaries. If it is decided to use a battery, then the motors should be of the d.c. type, and I think it is very desirable that all the motors should be of one type. I think the mixture of a.c. and d.c. motors, which several of the schemes show, should be avoided. There is no gain in reliability obtained by installing an a.c. and a d.c. motor as alternatives, as compared with two a.c. or two d.c. motors, provided these are supplied from different sources, and the advantages in maintenance and the reduction of spare parts obtained by adopting one uniform type of motor are great. This line of argument seems to lead to Scheme 7 as being the most suitable for this class of station where the final distribution is by means of direct current. Where the low-tension side is alternating, I should prefer to use a.c. motors throughout, and this is done only in Scheme 5, the details of which are only suitable for a very large station. I think there is also a tendency towards too great complication on the high-tension side. Of the five generators, Nos. 1, 2 and 3 are shown feeding on to separate sections of the high-tension busbars, but Nos. 4 and 5 have to share one section between them. In order to make all the switchgear uniform I think that it would be worth going to the expense of an extra oil-break switch and reactance, so allowing every generator to feed its own section of the main busbars. Then the high-tension sub-busbars are also divided into four sections, although these are fed by five alternators, and feed on to two transformers. I do not see the reason for this, and in any case are these sub-busbars really necessary? They entail a considerable expense for switchgear and will take up a good deal of space. Could not either of the two transformers be fed by any generator by means of a simple arrangement of selector switches? Another point of interest is the tendency towards the use of self-contained units. In the boiler house for a long time past the superheater in the main flue has been split up and erected in sections, each being an integral part of the boiler to which it is attached. The same thing has happened more recently to the economizer, which is now often fitted over the boiler of which it practically forms a part. The fans and the drive for the stoker gear are being dealt with similarly, and it is just a question whether we should not discard the pump room, fitting a feed pump to each boiler and so making it a complete self-contained unit. This would mean that the feed pumps would probably be motor-driven, and it would have the advantage of transferring these auxiliaries from the authors' Type (*b*) to Type (*c*), with a corresponding reduction in the necessity for spares.

**Mr. W. B. Hird:** I shall confine myself to one or two particulars where it seems that the opinions expressed are at variance with what one would expect from the experience of general users of electric plant as opposed to central station engineers. One point in particular is the distrust which the authors seem to have for d.c. as compared with a.c. motors. Whilst it is generally true that the a.c. motor is in some respects a somewhat more robust machine than the d.c. motor, I still think that the stress which has been put on the extreme cost of maintenance and on the troubles experienced with commutators and brushgear is exaggerated and is not borne out by the experience of the general user, who finds little to choose between the two classes of motors. I am by no means advocating the use of d.c. motors in central stations against the considered opinions of the central station engineers who have already spoken, but what I do suggest is that the real reason for their preference for a.c. motors lies in the difficulties and complications entailed by providing a special d.c. supply rather than in any inherent defect of the d.c. motor. The other point which I wish to make has already been touched upon by Mr. Christie, and that is that it seems as a matter of principle that the mixing of d.c. and a.c. machines for the same job on the same plant should be deprecated. If there are two motors to do the same job, and one is a.c. and one d.c., it is almost certain that one or other will prove to be the more convenient, and that one will be used regularly and the other only as a stand-by. I should think that it is the experience in central stations, as in most places, that if one has an emergency set standing by, waiting for an accident to happen, when the accident happens the emergency set always refuses to do its job. If the emergency set is to be useful, then it must have its fair share of the work to do. Apart from that, the number of spares which have to be carried is duplicated, and that again is another objection to the mixing of the two types. Against these objections the only advantage is the fact that there are available two entirely distinct systems, either of which remains unaffected by any breakdown, however serious, on the other, but two entirely separate systems can be devised on either alternating or direct current without any necessity for calling the other into use.

**Mr. W. Ross:** Regarding the various schemes described by the authors, to my mind the most attractive is Scheme 5, i.e. special windings on main transformers, or, if the switchgear is on the low-tension side, unit transformers connected direct to alternator terminals, a house turbine being installed for starting-up and for such duties as testing long-distance feeders through transformers. The simplicity and robustness of the induction motor is a great attraction, also the fact that if pulled up suddenly the motor will come up to speed again in most cases without suffering any damage. At the present time most supply authorities are endeavouring to limit the d.c. distribution on their systems, and it is surely their policy to show what can be done. Regarding the danger of synchronizing the main generators through the special windings, Messrs. Reyrolle arrange two switches to control the two supplies, these switches being coupled together so that both cannot be in circuit at the same time. In starting up, the auxiliaries are run from a substation transformer, and, when the machine is on load, one movement of the switch handle opens the substation switch and closes that on the special winding. The lack of speed regulation is only noticeable in two cases, fans and circulating-water pumps, and, although throttle regulation may not be the best, I think it would be justified by the simpler and more robust gear.

**Mr. J. S. Thomson:** In these days of high-pressure and high-temperature steam I should be inclined to keep the steam-pipe system down to the very smallest and to use electricity for all auxiliaries throughout the station, with the exception of the boiler feed-pumps and perhaps the condenser air-ejectors. For the boiler house I think that three-phase motors are the best all-round proposition. I look upon the boiler house of one of these large stations as being very much as an outside consumer, and I should supply it through duplicate transformers exactly in the same way as an important consumer. I should like to know whether it is a rare occurrence for the whole station to be shut down through outside faults. The authors say that in connection with large turbines of 25 000 kW two separate circulating pumps and air pumps are necessary. I take it that it is for construction purposes that these have to be split up. Assuming that they have to be split, I should imagine that supplying one of them off the general system and the other from the alternator terminals direct would give a reliable scheme. Another point is the difficulty in starting up if totally shut down. I have no experience of these large sets. The authors might say what the size of the house turbines would be for a station equipped with five 25 000-kW sets, and how they would start these up if entirely shut down. I think there is a good deal of unnecessary complication in some of the schemes. The great thing to my mind is to make the system as simple as possible. Simplicity is better than cross connections and a multiplicity of machines.

**Mr. A. P. Robertson**: I think that we may consider the emergency lighting of the station to be one of the important auxiliaries, and I believe that the only method of providing for this is by means of a battery. There should be a perfectly reliable automatic change-over switch, so that in the event of anything going wrong with the main supply the emergency lights at once come in automatically. It does not take a very large battery to do this work, and the lights ought to be fixed in those positions where illumination will be required. In Glasgow we have these lights installed in all stations, and, although it has unfortunately been called on a few times lately, it has never failed us. The battery ought also to supply the trip coils of the switches. I think that the main switches should all be tripped from an independent source, i.e. a battery, and not from the supply alone. I have known cases where switches were tripped from the main supply through transformers, and where they have failed owing to the voltage being so much reduced that the current was not strong enough when the actual fault came on. Regarding the coupling-bolt breakages, I have seen some very severe knocks on machinery and bolts have been twisted slightly. I remember a 3 000-kW turbo-alternator being switched in out-of-phase, in emergency. That machine ran for over a year before anybody found out that the coupling bolts had moved $\frac{1}{8}$ in., but still the supply was kept going, and, after all, that is the main thing. I do not think that the shearing of two or three coupling bolts matters much. Referring to the change-over switch, mention was made of the danger of leaving two systems coupled up. That might be overcome by bringing out a relay which would come into operation after the two systems were synchronized, and which would only stay in for a short time and then trip either one or the other. Another suggestion is to have the no-load releases on the auxiliary motors made with a time-lag. This is not quite so drastic as the Newcastle Electric Supply Company's coupling of motors through solid links, but possibly it would work quite well. Regarding the merits of d.c. and a.c. motors for driving, I think that a.c. motors ought, if possible, to be used in every case, as the work entailed in looking after commutators is very great compared with that required for a.c. motors. Direct-current motors have the advantage of having better speed regulation, but in many cases this can be got over by throttling on circulating-pump motors and by other devices on different plant. Unfortunately we are tied to d.c. supply in many cases, but where there is an a.c. supply I believe that it would be better in almost all cases to use a.c. motors. In Glasgow we have many rotary converters, and from March to September two gangs of men are employed constantly in grinding and looking after commutators, which shows what a great amount of maintenance the latter involve.

**Mr. A. G. Norris** (*communicated*): Ten to fifteen seconds seems a very short time to run up and put on the bars a turbine of even special construction. With regard to the special switching mentioned, it appears possible that synchronizing under these conditions might cause sufficient disturbance to the auxiliary circuit to trip some or all of the plant fed from it. In any case the shock to the auxiliary circuit would be more or less severe, the severity depending on the relative sizes of the incoming machine and the plant on load. Referring to the possibility of running up the auxiliary plant together with the turbine feeding it, it is not likely that a vacuum would be obtained under these conditions much before the main set reached full speed. In this case the low-pressure end would attain a fairly high temperature, as also would the main condenser if not provided with a sluice valve, and distortion of the casing would be likely to occur unless the set had been specially designed with a view to running up on atmosphere. There is further the risk of fracture of metal at the low-pressure end due to the sudden cooling which takes place when the vacuum temperature is reached. In the summary of Scheme 4 I notice that the authors describe the arrangement as efficient and reliable in operation, but in classifying the various schemes they say that Scheme 4 is an example of what to avoid. The authors' statement of failure of plant designed for industrial use when operated for long periods without a break is interesting. It is usually accepted that plant tested for a continuous period of six hours, or so, under its designed conditions reaches its steady working temperature in that time. It would appear, unless the authors have been unfortunate in their choice of plant, that much longer periods of testing would be necessary to ensure thorough reliability. A good deal of industrial plant runs under much more unfavourable conditions than those obtaining in a large power station, and in the case of some few industries is required to run continuously for fairly long periods without a stop. The authors' suggestion that the quick changing-over of induction motors from one circuit to another has resulted in the breaking of coupling bolts is surprising. The maximum shock sustained by the motor could not exceed that caused by directly switching-in the standing motor, and unless the change-over switch was operated very slowly the fall in speed of the motor would be very slight, and the shock due to switching correspondingly reduced. If the authors have had much trouble due to the change-over it would be interesting if they would say whether in their opinion it was due entirely to switching-over and not to faulty design of couplings and/or bolts, presuming that the switching operation was quickly carried out.

**Messrs. L. Breach** and **H. Midgley** (*in reply*): We note Mr. Bishop's comment regarding the grouping of the water-extraction pump in Type (*a*) when the air pumps are steam ejectors with intermediate coolers. We have given this question careful consideration, and we think that on the whole the change in classification is not necessary for the following reasons: Although the second stage of the ejector alone would, with a free exhaust, be able to maintain about 80 per cent of full vacuum, yet, in the event of a failure of the intercooler water, the second stage would then have to deal with the steam from the first stage, so that there would almost immediately be a considerable fall of vacuum. However, for use when starting up, a connection to the intercooler is usually made from the town's main or some such similar source, and it is suggested that in the circumstances under consideration it would be possible to turn on the alternative supply to the intercooler; this would mean that there would be a further delivery of water from the intercooler back to the condenser through the siphon pipe, so that the water would rise in the condenser more quickly than normally, consequently reducing the time for which the water-extraction pump could be out of action, but it should be possible for this pump to stop for periods up to 5 minutes with a reasonable chance of restarting before a failure of vacuum occurred. The question of the supply to the control circuits has been dealt with in the reply to Mr. Brazil in the London discussion. Whilst we consider that, generally speaking, contactor gear is not justified, we agree that in special cases, such as that of the circulating pumps at the Dundee station, its use is highly desirable.

In reply to Mr. Mitchell, the reference to Fig. 8 is on page 833, under the heading: "Arrangements of condenser auxiliaries." Our reply to Mr. Hamilton in the Liverpool discussion should also be read when this figure is being considered. We would refer Mr. Mitchell to the reply to Mr. J. S. Highfield in the London discussion as to the cost of a battery capable of carrying the load of half the station auxiliaries. In regard to the choice between a.c. and d.c. motors, since writing the paper it has come to our notice that one crane designer considers d.c. motors to be much more satisfactory for this work, it being claimed that only with this type can the necessary delicate control be obtained. The placing of Scheme 5 in the second grade is not because of its inclusion of the special winding on the main transformer, but because of the change-over switch. It would appear to us, especially in view of Mr. Mitchell's remarks, that a scheme embodying the special winding could be evolved which would be as satisfactory as any of the schemes included in the paper. We note with interest the information given by Mr. Mitchell in reference to the modification of the arrangements for the auxiliary supply at Dalmarnock.

Mr. Christie suggests that it is a waste of energy to consider proposals for auxiliaries until the system of generation and distribution has been arranged, but we would point out that it is only by reviewing the systems of auxiliary supply available that it is possible to make a sound choice, and the aim of the paper is to present the various alternatives rather than settle on any definite scheme. We would suggest that it is now generally accepted that the supply to the auxiliaries should be kept absolutely separate from the distribution system, so that any fault on the distribution system occurring outside the station may not endanger the supply to the auxiliaries. The number of sections into which the high-tension busbars are divided is a matter rather beyond the scope of the paper. The question of selector switches for the high-tension supply to the auxiliary transformers is dealt with in the reply to Mr. Robinson in the Liverpool discussion. We cannot agree that under any circumstances may the boiler feed-pumps be transferred to the class which can stop for 5 minutes; in fact, if any change were made in their classification it should be to include them in the class which must not on any account stop.

In reply to Mr. Hird, we would state that the only case that we put forward in which two motors are installed, one for normal working and the other for stand-by purposes, is for the stoker motors. In all other cases in which there are duplicate motors both are intended to be on load at once and therefore the difficulty of the second set refusing to work in emergency should not arise.

The splitting up of the circulating-water extraction pumps for 25 000-kW units, mentioned by Mr. Thomson, is to a certain degree advisable for constructional reasons, and this being so such an arrangement is all the more justifiable for the sake of reliability of supply. The size of the house turbine for a station containing five 25 000-kW sets would depend upon the number of house sets installed and what other provision is made for auxiliary supply, but it is quite simple to calculate the size in view of the information given in the diagrams as to the powers for the various auxiliary motors.

We agree with Mr. Robertson that tripping circuits should be operated by direct current so that a battery can be employed when necessary, and that power for these circuits should, as stated in the reply to Mr. Brazil in the London discussion, be transferred to Type (*a*).

# THE COMPOUND CHARACTERISTIC IN REGENERATIVE BRAKING WITH DIRECT-CURRENT TRACTION.*

By M. G. Say, M.Sc., and H. G. Frampton, Students.

(*Paper first received* 30*th November*, 1922, *and in final form* 5*th April*, 1923.)

SUMMARY.

This paper deals with a particular form of regenerative braking for d.c. trains, effected by the application of a differential compound field excitation to the traction motors. Speed/torque and speed/current curves are derived mathematically and experimentally, and are compared. A peculiar property of the speed/torque characteristic is a pronounced maximum value, to ignore which might be very serious.

## INTRODUCTION.

For the proper control of electric trains by regenerative braking, the traction units must possess both mechanical and electrical stability. Mechanical stability entails a rise of braking torque with increase of speed, and the avoidance of sudden changes in this torque. Electrical stability requires insensibility to fluctuations in line pressure, and a wide speed-range.

The pure shunt connection is practically unsuitable for automatic regeneration, since any speed-change requires a corresponding adjustment of the field flux to maintain the correct value of the voltage. Also, since the shunt motor has not been widely adopted for train haulage, it need not be considered here. The series machine has been found to be eminently suited for driving, and also for rheostatic braking, but is not inherently adapted for returning power to the line since the E.M.F. generated depends on the speed and load. For the purpose of regenerative control some simple modified connection permitting the use of series motors becomes essential. The differentially compounded arrangement has been used to supply the need, and it is the authors' intention in this paper to examine how far the regenerative action thus obtained is stable.

Compounding usually implies the use of two distinct exciting currents in separate windings, as indicated in Fig. 1. Here the armature (A) and field winding (F) are shown in the normal series connection as for a motor, while a second field winding (f) is supplied with the separate "shunt" exciting current $I_c$, by means of an exciter, Ex (the field arrangements of which are omitted for clearness). The regenerated current is $I$, so that if F and f are connected differentially the field flux of the generator will be due to the difference of the M.M.F.'s produced by $I_c$ and $I$. Thus a differential compound characteristic is obtained during regeneration.

In practice, owing to space limitations and in order to reduce losses, $I_c$ and $I$ are superposed in the one field winding. Only slight modifications are introduced thereby, as shown in Fig. 2. Here the exciter again carries the current $I_c$, and the field winding (F) carries the difference ($I_c - I$) when generating, or the sum when motoring with the same connections. In the latter condition $I$ is reversed, $I_c$ and $I$ acting cumulatively. The exciter field connections as adopted are given in Fig. 2: they consist of a series field ($F_s$), and a shunt field ($F_e$) in series with an adjustable rheostat. The exciter itself is compounded differentially during regeneration and cumulatively if used during driving conditions. Normally Ex is cut out when A operates as a motor.

The problem of adapting the series motor to regenerative braking at constant voltage reduces to this: The E.M.F. in the armature of the series traction motor when the latter is producing torque (i.e. while driving) is in such a direction as to oppose the terminal pressure. For the purposes of regeneration the main current must naturally reverse, and this entails a reversal of the E.M.F. induced in the armature if normal connections are retained. Under these conditions regeneration is, of course, impossible, and means must be found to maintain the induced E.M.F. in its original direction. To do this we must therefore supply an exciting current $I_c$, acting in the field winding only, which will maintain the induced E.M.F. In the compound connection both currents are allowed to flow in the field winding in order to obtain stability: this means that the separate exciting current must obviously be greater than the regenerated current at all times during regeneration. It will be shown later in the paper that this is accomplished automatically.

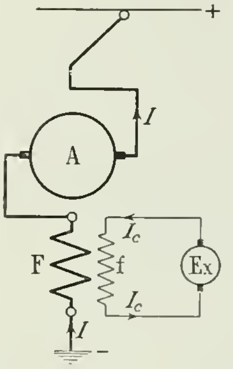


FIG. 1.—Differentially compounded generator with separate field windings.

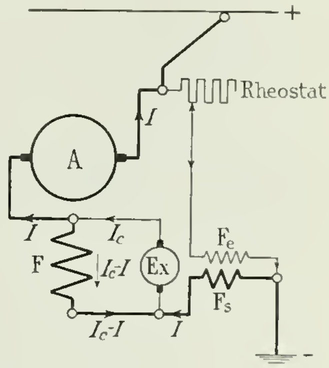


FIG. 2.—Differentially compounded generator with single field winding.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

### THEORY.*

The characteristic curves for a series traction motor operating as a generator connected in this way can easily be deduced mathematically. The following symbols refer to the diagrammatic representation of the motor in Fig. 3.

Let $V$ = constant line pressure (or applied voltage per motor if there are groups of motors in series).
$E$ = rotational E.M.F. generated in the armature (A).
$r$ = resistance between terminals of the armature (A).
$R$ = resistance of the field winding (F).
$N$ = armature speed, in r.p.m.
$I$ = current returned to the line.
$I_c$ = adjustable constant exciting current supplied to the field winding (F) by an exciter (not shown in Fig. 3).

Recuperation is effected by switching in the current $I_c$ of a value suitable to the speed, and the conditions under which this obtains must now be examined.

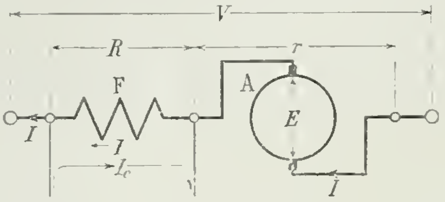


FIG. 3.—Simplified diagram of differentially compounded generator.

When regeneration is in progress, the electrical conditions are such that the induced E.M.F. is

$$E = \frac{p}{a} \times \frac{N}{60} \times Z\Phi\ 10^{-8} \text{ volts}$$

Assuming a straight-line magnetization curve, then

$$E = kN\Phi = K_1N(I_c - I) \quad . \quad . \quad . \quad . \quad (1)$$

Also, from Fig. 3 :—

$$E = V + rI + RI - RI_c = V + rI - R(I_c - I) \quad (2)$$

$$\text{Thus } E = K_1N(I_c - I) = V + rI - R(I_c - I) \quad . \quad (3)$$

When $I = 0$, Equation (1) reduces to :—

$$E = K_1N_0I_c = V - RI_c \quad . \quad . \quad . \quad . \quad (4)$$

where $N = N_0$ = speed at which the machine neither takes nor produces current. If $I$ is positive, or $N > N_0$, we have regeneration conditions; if $I$ is negative, or $N < N_0$, the machine acts as an ordinary compound-wound motor. The value of the constant $K_1$ is, from Equation (4) :—

$$K_1 = E/(N_0I_c) = (V - RI_c)/(N_0I_c) \quad . \quad . \quad (5)$$

As stated above, $I_c$ can be adjusted to any required constant value. From Equation (3), by rearrangement we have :—

$$NI_cK_1 - NIK_1 = V + I(r + R) - RI_c$$

$$\text{Hence } I = \frac{NI_cK_1 - V + RI_c}{R + r + NK_1}$$

$$= \frac{(N/N_0)(V - RI_c) - (V - RI_c)}{R + r + NK_1} \quad \text{[from Equation (4)]}$$

$$= \frac{N - N_0}{N_0} \times \frac{V - RI_c}{R + r + NK_1}$$

$$= \frac{K_1I_c(N - N_0)}{R + r + NK_1} \quad \text{[from Equation (5)]} \quad . \quad (6)$$

The mechanical power converted into electrical power is :—

$$\eta NT\frac{2\pi \times 746}{33\ 000} = EI$$

or

$$EI = \eta NTK_2 \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where $T$ = braking torque in pounds-feet.
$\eta$ = efficiency of the traction motor as a generator, without the copper losses.
$K_2$ = 0·142.

Hence the braking torque is :—

$$T = EI/\eta K_2N = \frac{NK_1(I_c - I)I}{\eta K_2N} \quad \text{[from Equation (1)]}$$

$$= \frac{K_1}{\eta K_2}\left[I_c - \frac{K_1I_c(N - N_0)}{R + r + NK_1}\right]\left[\frac{K_1I_c(N - N_0)}{R + r + NK_1}\right] \quad \text{[from Eqn. (6)]}$$

$$= \frac{K_1^2}{\eta K_2} \times \frac{I_c(N - N_0)(V + I_cr)}{(R + r + NK_1)^2}$$

$$= \frac{K_3}{\eta} \times \frac{(N - N_0)}{(R + r + NK_1)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

$$\text{The constant } K_3 = \frac{K_1^2I_c(V + I_cr)}{K_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Equations (6) and (8) are thus quite general and involve but one assumption, viz. a straight-line magnetization, which may introduce an error.

If $R$ and $r$ be neglected, and the efficiency assumed to be unity, then Equation (6) for the current becomes :—

$$I = I_c\frac{N - N_0}{N} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

and Equation (8) for the torque becomes :—

$$T = \frac{V}{K_2}I_c\frac{(N - N_0)}{N^2} = \frac{E}{K_2}I_c\frac{(N - N_0)}{N^2} \quad . \quad . \quad (11)$$

The torque and current curves for these ideal conditions are of the general shapes shown in Figs. 4 and 5.

Considering the current curves (similar to those shown dotted in Fig. 5) it will be seen that as the speed rises, the current increases steadily, approaching the value $I_c$, but having no maximum value at finite speeds. This can readily be shown by differentiating Equation

---

* It is assumed always that there is some apparatus connected to the line ready to absorb the regenerated power. Otherwise the conditions are quite different and regenerative braking is not possible.

(10) and equating the result to zero, when the following condition for maximum current is found :—

$$\frac{d}{dN}I = \frac{N - (N - N_0)}{N^2} = \frac{N_0}{N^2} = 0$$

Since $N_0$ has a finite value, then $N = \infty$. Inserting this condition in Equation (10) we have, when $N = \infty$, $I = I_{max.} = I_c$. This is to be expected, since at infinite speed only an infinitely small value of field flux (dependent on $I_c - I$) is required to produce the correct value of the E.M.F., $E$.

The torque curves (similar to those shown dotted in Fig. 4) exhibit a peculiar and unique shape. The fact that there are definite maxima brings out at once the disadvantage of this method of energy recuperation. For any given value of $I_c$, as the speed rises (e.g. when running down a gradient) the braking torque first increases until a particular speed is reached, after which it decreases, although not so rapidly as it rose. The speed at which maximum torque occurs (under the assumed ideal conditions) is found from Equation (11) by differentiation :—

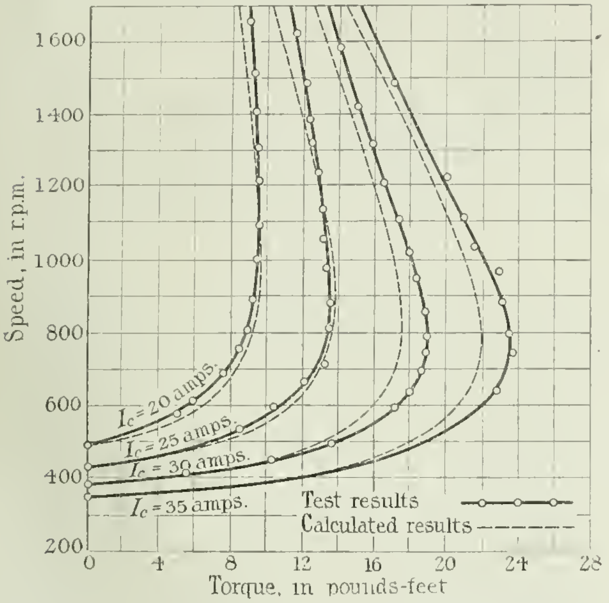


FIG. 4.—Torque/speed curves when regenerating, for four constant values of $I_c$. (*Note :* The calculated curves are based on the assumption of a straight-line magnetization )

$$\frac{d}{dN}T = \frac{d}{dN}\left[\frac{(N - N_0)}{N^2}\right]$$
$$= \frac{2N(N - N_0) - N^2}{N^4}$$
$$= \frac{N - 2N_0}{N^3} = 0$$

Hence $N - 2N_0 = 0$, or $N = 2N_0$ is the speed for maximum torque, i.e. *the point of maximum torque is reached when the speed has risen to twice that at which regeneration commenced.* For example, if $I_c$ is adjusted so that regeneration is begun when the train speed is 20 m.p.h., the maximum retarding force will be experienced if and when the train speed reaches 40 m.p.h. The value of the maximum torque may be found by substituting $2N_0$ for $N$ in Equation (11).

$$\text{Thus} \quad T_{max.} = I_c\frac{E}{K_2} \times \frac{N - N_0}{N^2} = \frac{E}{K_2}I_c\frac{2N_0 - N_0}{4N_0^2}$$
$$= \frac{E}{K_2} \cdot \frac{I_cN_0}{4N_0^2} = \frac{E}{4K_2} \times \frac{I_c}{N_0}$$

$$\text{Therefore} \quad T_{max.}N_0/I_c = \text{constant} \quad . \quad . \quad . \quad . \quad (12)$$

or since, under ideal magnetic conditions, $I_cN_0$ is a constant, and equal to $E/K_1$, then

$$T_{max.} = \frac{E^2}{4N_0^2K_1K_2} = \frac{K_1}{4K_2} \times I_c^2 \quad . \quad . \quad (13)$$

The relation between $T_{max.}$ and $N_0$ is important, and indicates that the value of the maximum torque falls off very rapidly as the separate excitation $I_c$ is decreased (i.e. as $N_0$ is raised).

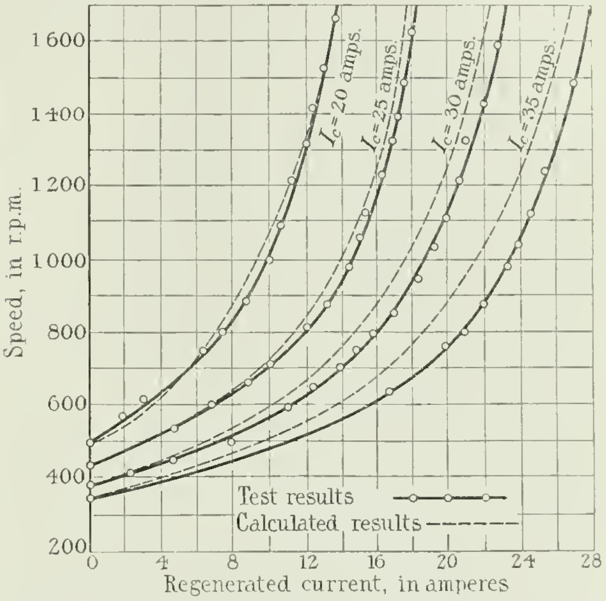


FIG. 5.—Current/speed curves when regenerating, for four constant values of $I_c$. (*Note :* The calculated curves are based on the assumption of a straight-line magnetization.)

Another point worthy of note is the value of the regenerated current when the torque is a maximum : $N = 2N_0$ is the condition for this, and inserting it in Equation (10) gives the result that when $T = T_{max.}$ then $I = \frac{1}{2}I_c$.

The presence of a point of maximum torque is important from a practical point of view. If a train has passed the speed at which braking is a maximum, and if it continues on the same down-grade, it will accelerate further unless controlled mechanically. Indefinite acceleration might open the circuit-breakers (if such are provided) owing to the continued increase in regenerated current. If this occurs, all electrical retarding force is destroyed, perhaps with grave results to the train. The breakers might be kept in if the separate excitation $I_c$ is reduced, but this materially decreases the braking torque also, as Fig. 4 will show. Further, the speed of the train, if allowed to increase by coasting before braking is applied, might attain a value beyond that for which the circuit breakers are set. In this case also electric braking would be impossible.

In the light of this, the following extract from the *Electric Railway Journal* of 21st August, 1920, is significant.* It concerns a freight train on the Chicago, Milwaukee and St. Paul Railroad, Rocky Mountain Division, on a long 2·2 per cent grade stretching from Boylston, Washington, to Beverley Junction, a distance of nearly 20 miles. The train consisted of 58 loaded freight cars, with an electric locomotive in front, and a Mallet steam locomotive on the rear. Beginning the descent, "the engineer, who was an experienced man, allowed his train to gather momentum up to a point where regenerative braking in parallel could be cut in. The permissible speed for cutting in the motors for regenerative braking is from 15 to 20 m.p.h. Apparently the engineer waited for the speed to exceed 15 m.p.h., but failed to cut in his regenerative switches until the speed had reached at least 20 m.p.h., and the breakers would not hold. The confusion in his mind, resulting from the operation of the overload relays, caused a loss of action on his part for perhaps a fatal half-minute, during which time the speed of the train kept rapidly increasing. The engineer then made a service application of his automatic air brakes, but this did not check the train. He tried to cut in the regenerative system a time or two, but the speed was too high and the breakers would not stay in. The service application of air was then released and an emergency application made, but the speed must have reached 35 m.p.h. by this time, and the brakes had no effect in checking the train."

The train remained intact until 12 miles down the hill, when the Mallet engine on the rear broke loose. Released from the retarding influence of the latter, the train rapidly gathered speed. From this point to the bottom of the grade the freight cars were derailed in sections, leaving the electric locomotive completely released from the train. The locomotive came to rest 3 miles past the end of the grade. The account concludes with the statement: "the entire responsibility is placed on the engineer, who failed to cut in his regenerative braking until the speed had become excessive."

On an undulating track, a train can automatically "motor" and regenerate alternately without any change of connections or adjustment, maintaining a speed varying within fairly narrow limits. In this respect a train operated on the compounded principle is comparable with a train equipped with three-phase induction motors.

## TEST-RESULTS.

In order to substantiate the assumptions made in the theory, tests were performed on a 10-h.p. series motor specially arranged for torque measurement, and regenerating into a secondary battery of 102 volts "line" pressure. Results obtained for four different constant values of $I_c$ are shown in the full-line curves in Figs. 4 and 5, the dotted-line curves being the results calculated from Equations (6) and (8). It was necessary to do these calculations point by point for the torque, owing to the variation of efficiency at different currents and speeds. Mean values were assumed for the armature and field resistances. An abridged example of the method is given below.

Field resistance $R = 0\cdot17$ ohm.
Armature resistance $r = 0\cdot35$ ohm.
$R + r = 0\cdot52$ ohm.
Constant value of $I_c = 30$ amperes.
Speed for $I = 0$, $N_0 = 380$ r.p.m.

Then $K_1$, from Equation (5),

$$= \frac{102 - 5\cdot1}{11\,400} = 0\cdot0085$$

and $K_3$, from Equation (9),

$$= \frac{(0\cdot0085)^2 \times 30 \times 112\cdot5}{0\cdot142} = 1\cdot71$$

TABLE 1.

*Values of $T = f(N)$ and $I = f(N)$, for $I_c = 30$ amperes.*

| $N$ | $N - N_0$ | $R+r+NK_1$ | $I$ from Eqn. (6) | $\eta$ | $(R+r+NK_1)^2$ | $T$ from Eqn. (8) |
|---|---|---|---|---|---|---|
| r.p.m. | r.p.m. | | amps. | % | | lb.-ft. |
| 500 | 120 | 4·77 | 6·4 | 71 | 22·8 | 12·7 |
| 600 | 220 | 5·62 | 10·0 | 75 | 31·7 | 15·9 |
| 800 | 420 | 7·32 | 14·6 | 78 | 54·0 | 17·1 |
| 1 000 | 620 | 9·02 | 17·5 | 79 | 81·5 | 16·6 |
| 1 200 | 820 | 10·72 | 19·5 | 79 | 115·5 | 15·4 |
| 1 400 | 1 020 | 12·42 | 20·9 | 78·5 | 155 | 14·5 |
| 1 600 | 1 220 | 14·12 | 22·0 | 78 | 200 | 13·4 |

The agreement between the full-line test curves and the dotted curves derived from the formulæ is fairly close, especially when $(I_c - I)$ is such that saturation of the magnetic circuit does not falsify the original assumption of a straight-line magnetization curve. The calculations might, of course, be effected by a point-to-point method, using the actual magnetization curve of the machine. This, however, is scarcely necessary, because $(I_c - I)$ is generally less than the full-load current and decreases as the speed rises.

It was shown for the ideal case that the maximum torque occurs at a speed $N = 2N_o$, and that the regenerated current at this speed is $I = \frac{1}{2}I_c$. The actual speeds and currents obtained in the test are given in Table 2.

---

* Although the authors, in view of their ignorance of all the factors and of the details of the system employed, do not presume to suggest that the results just deduced explain the reported disaster, it was due to Prof. W. Kummer's reference to this accident in his interesting article in the *Schweizerische Bauzeitung*, (1921, vol. 77, p. 139), that Dr. S. P. Smith encouraged them to investigate the problem of this form of regenerative braking.

TABLE 2.

*Test-values of $N/N_0$ and $I/I_c$.*

| $I_c$ | $N$ at $T_{max.}$ | $N_0$ | $N/N_0$ | $I$ at $T_{max}$ | $I/I_c$ |
|---|---|---|---|---|---|
| 20 | 1 100 | 497 | 2·21 | 10·25 | 0·513 |
| 25 | 870 | 425 | 2·05 | 12·4 | 0·496 |
| 30 | 800 | 380 | 2·10 | 14·7 | 0·490 |
| 35 | 750 | 350 | 2·14 | 17·6 | 0·502 |

The values of $N/N_0$ approximate to 2, the maximum deviation being about 10 per cent, while the values of $I/I_c$ lie very close to 0·5, the difference being in no case greater than 2·5 per cent. It has also been shown that for the ideal case the maximum torque is proportional to $I_c/N_0$, or that $T_{max.}N_0/I_c$ = constant [see Equation (12)]. The errors introduced by ignoring resistance losses and saturation are also investigated for the machine tested, and are shown in Table 3.

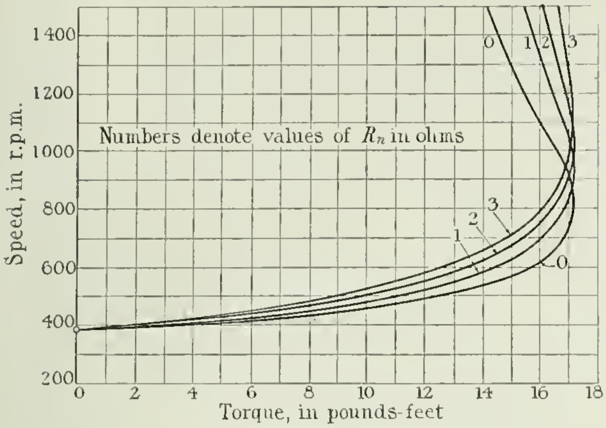


FIG. 6.—Curves showing the relation between torque and speed with constant separate excitation $I_c$ = 30 amperes, and for four values of notching resistance $R_n$.

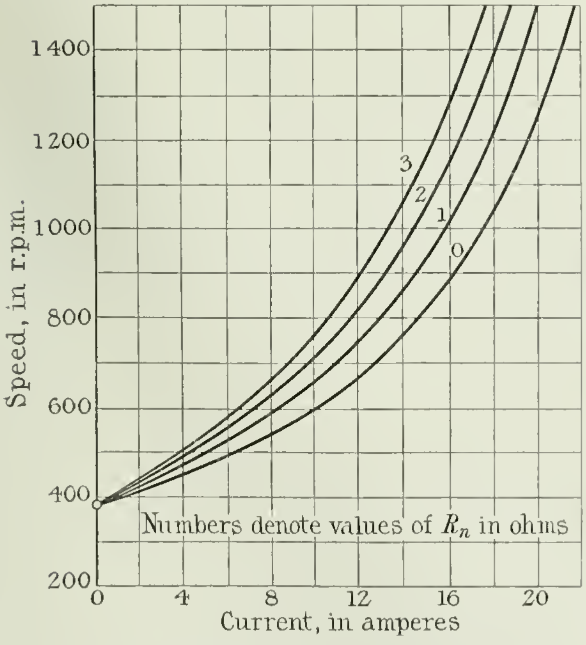


FIG. 7.—Curves showing current/speed relation with constant separate excitation $I_c$ = 30 amperes, and for four values of notching resistance $R_n$.

TABLE 3.

*Test-values of $T_{max.}N_0/I_c$.*

| $I_c$ | $T_{max.}$ | $N_0$ | $T_{max}N_0/I_c$ |
|---|---|---|---|
| 20 | 9·5 | 497 | 236 |
| 25 | 13·25 | 425 | 225 |
| 30 | 19·0 | 380 | 240 |
| 35 | 23·75 | 350 | 237 |

The maximum deviation from the mean value (234·5) of $T_{max.}N_0/I_c$ is only 4 per cent, thus showing that under actual conditions this quantity is practically a constant.

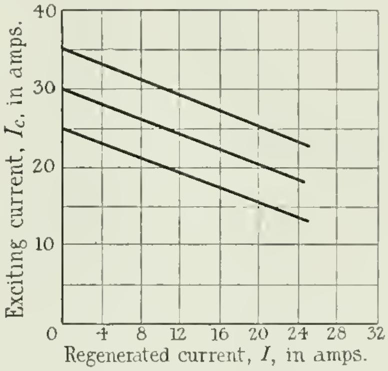


FIG. 8.—Assumed exciter characteristic for Figs. 9 and 10.

In a large traction motor, where losses have relatively less influence, even closer agreement might be expected. Where resistance notches are included in the main circuit for the purpose of providing easy braking steps, the ideal approximation will obviously not be so close, and the calculation must be based on the general formulæ in Equations (6) and (8), replacing $r$ by the term $(r + R_n)$, where $R_n$ is the extra resistance in circuit.

To indicate the influence of the inclusion of resistance in the main circuit, the curves in Figs. 6 and 7 have been drawn from Formulæ (6) and (8). As saturation has been shown to have but little effect on the results, these curves can be taken as being fairly correct. They are for the 10 h.p. motor previously mentioned, working with a shunt excitation $I_c$ = 30 amperes. Fig. 6 shows the torque/speed relation for four values of notching resistance $R_n$, viz. $R_n = 0$, 1, 2 and 3 ohms. The curve for $R_n = 0$ is, of course, identical with the dotted curve for $I_c = 30$ in Fig. 5. It will be seen that the values of the maximum torque in the four cases shown in Fig. 6 are practically equal, but the speeds at which these maxima occur vary considerably, being higher the greater the value of $R_n$. The current/speed curves in Fig. 7 indicate what might have been expected, i.e. that the current returned to the line at any particular speed is less as $R_n$ increases. This is, of course, due to the higher E.M.F., $E$, which the resistance necessitates. It can be seen that for practical use on railways a control utilizing both resistance notches and the variation of the separate excitation $I_c$ is useful and desirable.

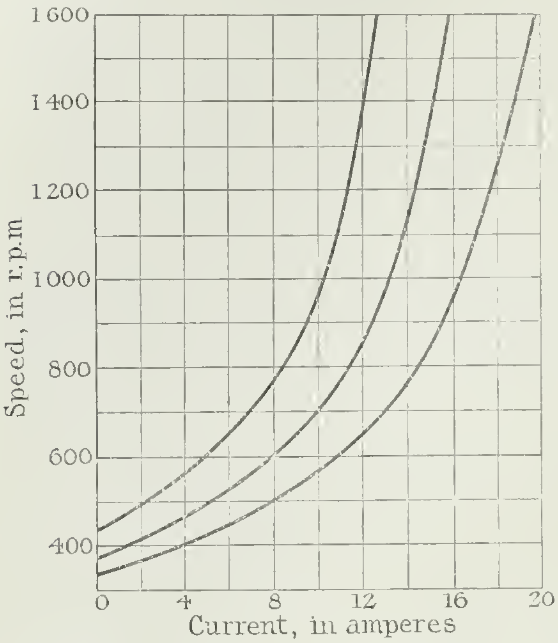


Fig. 9.—Effect of falling exciter characteristic on the current/speed curves (compare Fig. 5).

### Practical Considerations.

In practice, the actual calculations necessary to determine the braking curves are more complex than those entailed in the use of Equations (6) and (8): they take account not only of the proper magnetization curves but also of the characteristics of the exciter, which actually does not give a constant current. As the object of the paper is to give the fundamental principles in a simple manner, the authors will only indicate the effect of a varying exciting current.

For this purpose the braking curves have been calculated for the 10 h.p. motor tested, operating with the falling exciter characteristics shown in Fig. 8. The regenerated current/speed curves are given in Fig. 9, and the braking torque/speed curves in Fig. 10. It will be noted that the shapes of these curves are scarcely altered, the effect being only to reduce the higher values of torque and current. Similarly, the effect of a rising exciter characteristic would be in the opposite direction. In any case, the well-defined maxima exhibited in the torque curves with constant excitation retain their prominence, although in this case it is somewhat diminished. Just as it has been seen that the saturation of the magnetic circuit alters the braking curves to only a slight extent, so is it also seen that a reasonable exciter characteristic does not alter the *shapes* of these curves. The simple theory developed in the foregoing therefore has some value in indicating the safe limits to which this form of regenerative braking can be worked.

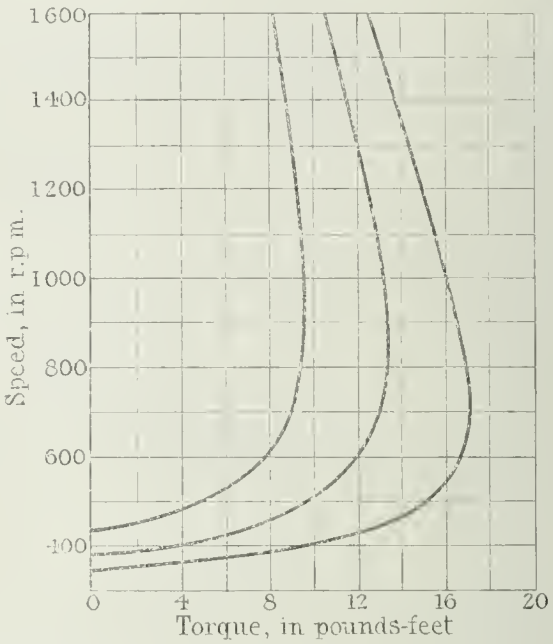


Fig. 10.—Effect of falling exciter characteristic on the torque/speed curves (compare Fig. 4).

The authors desire to thank Dr. S. P. Smith for his valuable assistance and advice.

# DISCUSSION ON

## "SOME PROBLEMS IN HIGH-SPEED ALTERNATORS, AND THEIR SOLUTION."*

### WESTERN CENTRE, AT CARDIFF, 5 FEBRUARY, 1923.

**Mr. J. W. Burr**: The author states that " the speed of the alternator, now being optional, is made low (500–750 r.p.m.), so that ordinary materials and low-speed construction may be adopted, with a view to reduced cost." I do not quite follow this, because we are told that it is possible to make alternators of high capacity run satisfactorily at high speeds. Does the author mean, for example, that it would be cheaper to run a 5 000 kW set through reduction gearing than to run it direct-coupled at 3 000 r.p.m.? I should like him to state the efficiency of the reduction gearing. Referring to high-speed machines, a year or two before the war I found it impossible to obtain a 1 000 kW exhaust turbine to run at 3 600 r.p.m. While great advance has been made in the size and speed of turbo-alternators, nothing seems to have been done to increase the generating pressure. In the early days the Deptford machines generated at 10 000 volts. Would it not be an advantage to generate at a higher pressure and to connect straight on to the transmission line, instead of through transformers as at present? I prefer the tunnel to the open-slot winding, if only for the reason that it is possible to obtain a voltage wave-form free from ripples. Trouble has been experienced on a distribution system with which I am connected, due to resonance caused by the higher harmonics. I do not like the idea of using a quick-break switch on the exciter circuit; even in cases of emergency I should prefer the slow-dying field.

**Mr. R. G. Isaacs**: I have been specially interested in the author's measurements of distortion in rotor end caps and can appreciate his difficulties. When one thinks of the effect of windage on a spark it is remarkable that he was able to get such close correspondence between results and calculations. An alternative to the method adopted is that developed, I believe, by Prof. Widdington, in which an oscillating thermionic valve circuit is used. It is well known that in a circuit of this kind a very small change in the capacity of the condenser used leads to a large change of distance between the plates of an air condenser. The rotor end cap forms one plate of the condenser and a small disc takes the place of the author's sparking point. By putting the oscillograph in the plate circuit, a plate which varies with the gap between the rotor and the disc can be obtained. Of course the oscillograph is calibrated with the motor at a standstill. This method is certainly simpler and, I believe, would give more accurate results. One of the minor difficulties in exciters is the failure to excite when started after the set has been shut down. Possibly the explanation is that given by the author. Another explanation suggests that the main field retains its magnetism longer than the exciter, weak alternating currents which may demagnetize the latter being generated in the rotor winding by the varying flux caused by the slots. If this latter explanation be correct, then a series winding will not help but will make matters worse. It seems to me that in the case of sets which have to be brought quickly into service it is generally worth while to provide separate excitation for the exciters. With regard to methods of ventilation and the closed air system described, there is one advantage which should be stressed, namely, the easier method of measuring the losses of the alternator thereby afforded; if the system comes into use, most valuable information will be obtained as to the increase with age of losses in alternators.

**Major E. I. David**: My experience suggests that in South Wales alternator troubles are confined to rotors and mechanical details. Possibly in the Parsons machines mechanical trouble is obviated by the use of rotors of small diameter, but the adoption of small diameters must lead to limitations in other directions. It strikes me that with these extremely long rotors the critical speed must be near the running speed. I have in service a rotor considerable greater in diameter than those of the author's machines, and its length is considerably less—about 36 in. diameter, active length 63 in., with a peripheral speed of 474 ft. per sec. as compared with 300 ft. per sec. of the Parsons machine. With regard to stator insulation, I gather from the author's remarks as to the method of winding that, after the preliminary heating, reliance is placed upon the elasticity of the oils in the varnish to meet the expansion difficulty, but as most of these are vegetable oils they will oxidize in time, thereby affecting the elasticity and leaving the insulator in a more or less brittle state. Has the author found that these oils do become oxidized and therefore hard? I certainly cannot agree with the author as regards closed slots. To lift a coil out of a slot about 2 in. deep is very different mechanically from pushing it through a slot 6 or 7 ft. long. The abrasion of the insulation caused in pushing it through endways must be considerably more than results from sliding it in sideways. In the case of the open slot there are only two joints per coil, whereas in that of the closed slot there are three joints at each end, or six joints per conductor, and it is well known that joints are a source of trouble; it is therefore preferable to eliminate rather than to multiply them. Then in the case of the open-slot machine a certain amount of elasticity is provided for copper expansion by the wooden wedge on the top of the coil; thus the insulating material is of solid construction and a better mechanical job is obtained than in the closed-slot machine. With regard to ripples, I have made during the past six months on an open-slot machine oscillograph tests which show ripples of only 3 per cent of the total value of the voltage on full load. This compares favourably with the 2·1 per cent for the closed-slot machine shown on the screen. The voltages between phases and also between phase and earth were measured. On open circuit this particular machine has a voltage wave absolutely without ripples both between phases and between each phase and the neutral. At full normal rating the phase-to-phase voltage is a pure sine wave without ripples, but there is a slight ripple corresponding to a third harmonic in the phase-to-neutral voltage, amounting to about 4·5 per cent of the fundamental. The system on which this machine was working was also tested and the ultimate phase-to-phase voltage was found to be practically a pure sine wave with a slight third harmonic in the phase-to-neutral wave when all machines were on load. With reference to the exciter shunt field, this is an extremely important matter when running a number of machines on busbars connected up by interconnected feeders. In the course of the experiments to which the author refers, what was the time usually taken for the field to die down when the circuit was opened, there being a discharge resistance of reasonable value across the switch terminals? Also, what would be the voltage produced in the rotor body in these circumstances as compared with that when the field was broken by a rotor switch with no discharge resistance? In South Wales there are in service very many machines having field-suppression switches connected up with the main circuit breaker. As regards the method of dealing with the question of reversed polarity, there is one objection to the compound winding which has not, I believe, been mentioned, namely, the consequent increase of the very difficulty to which the author has referred—the creepage of the exciter voltage when synchronizing. Owing to the fact that in this method one has a closed circuit, the exciter voltage will increase at a much greater rate with the compound winding than in a plain shunt machine. Therefore, the compound winding will have a tendency to make it still more difficult to synchronize. An arrangement which does not introduce this objectionable element is that of fitting the machine with stabilizing windings separately excited from a battery, which is usually available in a modern station. This field need take only a very small proportion of the total excitation of the exciter, and will rectify any reversal of polarity and also steady the machine at very light loads when working with a voltage regulator. With a standard-speed alternator there is sufficient difference in cost between a 3 000 r.p.m. turbine and a 5 000 or 6 000 r.p.m. turbine to provide a suitable gear between turbine and alternator. It is not absolutely necessary to run the alternator at 3 000 r.p.m.; in fact in some instances it is cheaper to use a fairly high-ratio gear and a salient-pole alternator running at speeds of 750-1 000 r.p.m. Mr. Burr also has mentioned this difference in cost between 3 000-r.p.m. machines and 750- or 1 000-r.p.m. machines. If gearing is to be introduced I think it is preferable to use a normal salient-pole alternator running at, say, 750 r.p.m. With regard to air cooling, it is particularly interesting that this matter has been advanced by the manufacturers. In a wet air-filter the temperature of the incoming air may be 50° or 60° F. and that in a dry air-filter of the oil type from 60° to 75° F.; but in the closed-circuit system, with water taken from the same source as the condenser water from cooling towers, the temperature is between 85° and 100° F. Has the author made any comparison between the cost of the new closed-circuit system compared with that of the old type? I was present recently at a test of a 20 000 kVA 3 000 r.p.m. set having a rotor of 36 in. diameter; the alternator was self-cooled, provision being made for cooling externally the two centre compartments, but the temperature was not found to be any greater. The efficiency of external-fan cooling must be higher than that with a rotor fan. An external fan is driven at the speed giving best all-round efficiency for its pressure and the volume of air, whereas both speed and diameter are rigidly fixed in the rotor fan, and no proper diffusion chamber is possible. In this particular machine the actual power taken for cooling under full-load conditions was about 240 kW.

---

* Paper by Mr. J. Rosen (see page 439).

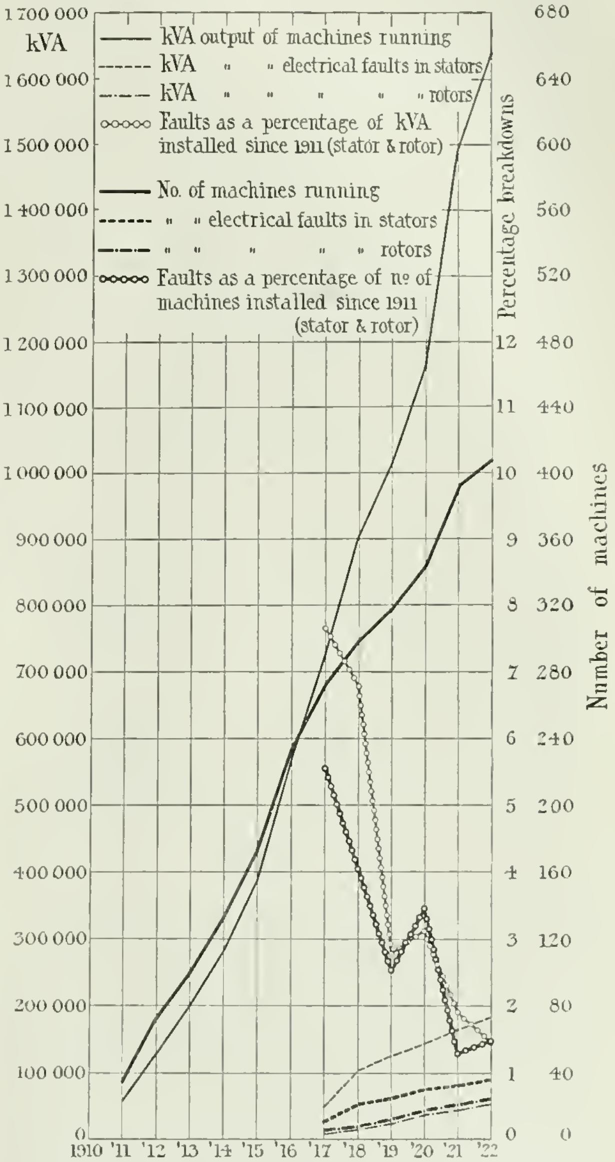
**Mr. W. A. Chamen**: In a year's time I shall be in a much better position to discuss the question of large alternators, for the South Wales Power Company are now installing a 15 000 kW machine. As regards cooling methods, I was anxious to use the closed-circuit system, but I thought it wiser not to do so at present; however, I have made provision for introducing it later. We have to deal with river water which in summer, and when the flow is not great, may reach a temperature of 80° F., whereas Messrs. Parsons will not guarantee sufficient cooling with a water temperature above 60° F. Perhaps with further knowledge and experience adequate cooling may be evolved in the future. The precaution has been taken to put in thermo-couples for measuring temperatures at different places on the alternator windings.

**Mr. W. J. Bache**: In reading the paper I was surprised that the author had not referred to the method of solving some of the problems by converting the high-speed into a low-speed alternator, but after he had read the paper I saw that he has been considering larger machines, perhaps, than are generally dealt with in this way. The author states that ventilation appears to be a limiting factor in designing for high speeds; ventilation, of course, is closely interrelated with insulation. With regard to temperatures, I should like to hear the author's opinion as to the practice which appears to be growing abroad of specifying a definite final figure that is not to be exceeded. The British practice is to specify so many degrees of temperature-rise. In this connection I am interested to learn from Mr. Chamen that he has incorporated thermocouples in his machine. Is this becoming a general practice, and, if so, down to what size and capacity is their use justified?

**Mr. C. G. Bevan**: I should be glad to know whether any particular difficulty has arisen with gear-driven turbo-alternators when used in stations with a widely fluctuating load.

**Mr. H. S. Ellis**: It is unfortunate that the maximum speed of most alternators is limited to 3 000 r.p.m., but I suppose that this must be put up with in view of the popularity of the 50-period supply in most districts throughout the country. However, I should like the author's opinion as to the probable maximum size and speed of turbines of the geared type and the advantages that would accrue from the use of such types for the driving of alternators, bearing in mind the lower steam consumption of the high-speed turbine as compared with the loss of power, etc., due to the interposition of gears. With regard to the suggestion that the hot air from the air-filters should be passed into the stokehold, no doubt we have all thought of how to make use of such hot air, but, however desirable it may be to do this, one has to bear in mind the cost of constructing suitable air ducts to convey such air to the furnaces. I quite agree with previous speakers that it is difficult to get river water at a sufficiently low temperature for use with air-filters, but doubtless some solution of the problem will be found before very long, and, provided efficient means can be found for cooling the water, I think that air-filters of the closed-circuit type have a great future before them. The author does not mention circulating currents in rotor shafts and their effect upon the journals. I have had considerable trouble from time to time as a result of circulating currents in connection with d.c. machines and rotary converters, but in all cases the difficulty has very largely been overcome by fitting a slip-ring at each end of the rotor. I have had no trouble with any alternator bearings, but in view of the author's remarks I should like to know if such trouble has been experienced elsewhere.

**Mr. G. A. Juhlin**: The figures given by the author showing the breakdowns experienced are of considerable interest, as it is only by such comparisons that one can judge whether satisfactory progress in the building of large plants is being made. Fig. J shows the record of the Metropolitan-Vickers Company, including the year 1922, and it should be noted that whereas the author deals with stator breakdowns only, this figure contains breakdowns on rotors in addition. The author makes a point of the ratio of the diameter of the rotor to its length. It is somewhat difficult to understand his reason for doing so, as the diameter is in general the criterion of the size of the machine, especially as the various ventilating schemes in use make the length of very little account from this point of view. The length is of importance only so far as critical speeds and mechanical strength generally are concerned. The author's remarks with regard to insulation and the stranded conductor are of considerable interest, but I do not think that his deductions are correct when he lays down the condition that the insulation should be flexible. It is at all times difficult to dogmatize on such a question, and it seems possible that the trouble experienced by the author is peculiar to the stranded cable because of its uneven surface, which allows mica to bed itself into the interstices between the individual strands; as the cable is wound helically there is a definite lock between it and the mica, causing the difficulties experienced. No troubles of this nature have been encountered, so far as I am aware, with ordinary straight copper bars insulated with hard-pressed mica, and I am certainly of the opinion that the pressed mica is more satisfactory. I think there is a serious drawback to the cable type of conductor in that it is necessary to use cotton covering on the individual strands, in my opinion an unsatisfactory insulation for large turbo-alternators. I consider that nothing but mica should be used for the embedded portion, and as far as possible it should be used on the end connectors. The author states that the plain solid forging has been found by experience to be the most satisfactory.



The following mechanical faults also occurred :—

1919 : 1 333 kVA rotor.
1919 : 6 250 kVA rotor.
1920 : 23 500 kVA stator.
1920 : 23 500 kVA stator.
1921 : 15 600 kVA rotor.
1921 : 13 300 kVA rotor.
1921 : Three obsolete rotors (total kVA = 12 340).
1922 : 15 600 kVA rotor.
1922 : 6 250 kVA rotor. (Old rotor : faulty bronze casting.)

Fig. J.—Number and output of turbo-alternators in service.

I have no doubt that those responsible for other types of construction such as the bolted-plate rotor would join issue with this finding, as it must be conceded that the latter type of rotor has been in operation for a considerable number of years without any difficulties occurring. I think one may say that a solid rotor is undoubtedly a sound contruction, but it cannot be said that it is the only type of rotor which may be regarded as satisfactory. The bolted-plate type of rotor is still being built by the Westinghouse Company of America at East Pittsburg, and units of far greater output than those contemplated in this country are under construction. I do not think it is necessary to revert to completely closed slots in order to avoid tooth ripples. The completely closed slot has the disadvantage that trouble is very liable to occur in the bridges due to overheating, and cases of such trouble have, I believe, occurred. This is, of course, obviated by introducing a small slot in the bridge. The author's remarks in connection with instability of exciters are of interest. There is no doubt that the compound winding overcomes the difficulties experienced with reversals of polarity. For the last 11 years we have fitted a compound winding on the exciters of large turbo-alternators, and no troubles have been experienced due to this cause. Saturation gaps have also been in use still longer, with the result that no difficulties whatever are experienced from instability at low voltages. I am interested to note that the author advocates the use of a field-breaking switch, and I agree entirely with him that this switch should only be used in the case of a fault in the machines. I consider that the field switch should only be employed in conjunction with the Merz-Price relay, which, of course, only comes into operation on the occurrence of an internal fault in the machine, when it is desirable to cut the field off as rapidly as possible.

**Mr. J. Rosen** (*in reply*): In reply to Mr. Burr, it is not proposed that gearing should be applied to all sizes of machines. Geared turbo-alternators have proved suitable for the smaller machines at 50 periods; for generating at 25 periods they can be made commercially up to outputs of 10 000 kW. The loss at full load with single-reduction gearing does not exceed 1½ per cent of the alternator output. In order to reduce the overall length of a turbo-geared plant, high-pressure and low-pressure turbines developing approximately equal power at full load are placed side by side and, coupled through pinions to the same gearwheel, run at their most economical speeds. This arrangement also has the advantage that it halves the width of the tooth face of the gear as compared with a single-pinion drive.

I have dealt with the question of alternators generating at higher voltages for coupling direct to the transmission line in reply to Mr. Selvey (see page 466).

Mr. Isaacs refers to the use of the thermionic valve and condenser for measuring the distortion on the rotor end caps. I have no doubt at all that the distortion could be measured accurately by this means; Mr. John J. Dowling has already considered the application of this principle to the dynamic balancing of rotors.

I am pleased to hear that Major David has had such little difficulty with alternator stators. In my own experience, certain stators developed weaknesses which, after thorough investigation, were finally eliminated, with the result that they are now equally as reliable as their rotors. I agree that in some respects the limiting of the rotor diameter has prevented faults which might have occurred if the rotors had been designed to run at higher peripheral speeds without having first obtained complete data of the difficulties.

As Major David is no doubt aware, the major portion of the deflection in a rotor is due to shear stress and bending stress, and occurs between the journals and the rotor body. Therefore the permissible journal diameter is the limiting factor; and the critical speeds of rotors of different diameters designed for the same output and speed are almost the same. Although there is a calculated critical speed on a 3 000 r.p.m., 20 000 kVA rotor made from a single forging, below its normal running speed, it does not become apparent on a well-balanced rotor, and the second critical speed has not yet been reached with such rotors when running up to 4 000 r.p.m.

Major David is correct in assuming that reliance is placed on the elasticity of the materials in the insulating varnish to meet expansion difficulties. At the temperatures at which the windings operate, the oils used in the varnish do not oxidize. By impregnation the air is excluded from the insulation, and therefore higher temperatures are permissible than when exposed to the atmosphere.

Conductors, after several years of operation, have been removed from the stators for examination and the varnish has been found to retain its original quality of flexibility. For pulling the conductors into position in the stator slots, liners of insulating material are provided, and, by the special steps adopted in winding, the conductor is very readily placed in position and there is no danger of abrading the insulation. As mentioned in reply to other speakers, it is not necessary to interfere with the remainder of the winding when replacing a conductor. Where "former" wound coils are used in an open slot and secured by wooden wedges, it is necessary to disturb several adjacent coils in order to replace any coil that may be damaged. With the tunnel construction a wooden wedge is also provided at the top of the slot, but its purpose is to protect the coil from the sand-blast action of grit being thrown out by the rotor.

I have dealt with the question of multiple joints in reply to Mr. Partridge (see page 466).

In view of the comments of various speakers, I have recently carried out a further series of tests on a 3 750 kVA alternator, and in these tests oscillographs were taken of the rate of fall of the stator voltage. They give a better criterion of the value of the switch for field suppression. The results are given in Table A, and will reply to Major David's question on this subject.

I have dealt fully with the series stabilizing winding on the exciter in reply to previous speakers. No difficulties have been experienced due to creepage of the exciter voltage, and there is no difficulty in synchronizing.

There is no necessity for the additional cost and complication of a separate source of excitation for stabilizing the exciter.

The water used in the coolers is normally taken from the cooling-water system of the main condenser, and the average temperature is below that given by Major

David, but even with cooling water at 80° F. I should still recommend the closed-circuit system of ventilation; it has been found that as all dirt and greasy matter is kept from the windings, the surface is more effective for cooling. This advantage offsets the disadvantage due to the higher cooling-water temperatures. On the question of the cost of the coolers I would refer Major David to my remarks in reply to Mr. Marshall on page 471.

I gather that the 20 000 kVA machine at 3 000 r.p.m., mentioned by Major David, was of Continental manufacture and was not run under normal conditions, but was run at the works on open-circuit and on short-circuit, and therefore the worst conditions of heating were not realized. For machines of this size at 3 000 r.p.m. I consider that an external fan is essential. On a Parsons alternator of the same output the power absorbed in the external motor-driven fan would only be 45 kW, as compared with the 240 kW with integral fans on the machine in question.

I agree with Mr. Chamen that, with the further experience now gained, coolers would be permissible on his water supply. At the time when the details of his 15 000 kW plant were under consideration I think he was very wise in adhering to a system of ventilation of which he already had experience; experience of coolers in service was then not very extensive. I have seen the lay-out of his ventilation system; it is a very simple one, and can be readily changed to the closed-circuit system if so desired.

TABLE A.

*Oscillograph Tests carried out on a 3 750 kVA Alternator.*

| Type of switch | Discharge resistance | Stator pressure, percentage of original value after 0·8 sec. | Rotor current. Time to reach zero | Rotor pressure | |
|---|---|---|---|---|---|
| | | | | Original value | Peak value |
| | ohms | per cent | secs. | volts | volts |
| Oil-break .. .. | — | 51 | 0·015 | 34 | 780 |
| Quick air-break .. | — | 51 | 0·05 | 34 | 250 |
| Air-break .. .. | 4 | 71 | 1·5 | 34 | 140 |
| Air-break .. .. | 0·4 | 85 | Reaches 72 % in 1·7 secs. | 34 | 38·5 |

In reply to Mr. Bache, it is certainly an advantage to specify a value for the average temperature of the stator windings, and this should not be exceeded.

Thermo-couples or embedded detectors are now being used on most large machines. They can be usefully employed on alternators above 3 000 kW, but whether the additional cost is warranted in the smaller unit depends upon the engineer and the staff available for making use of the figures so obtained. It is an expensive matter to install thermo-couples on machines, as, apart from the cost of the instrument and couples, many precautions must be taken in fitting them.

I can assure Mr. Bevan that geared turbo-alternators have been built and run in stations with widely fluctuating loads, and no difficulties have ensued.

I would refer Mr. Ellis to my reply to Mr. Burr on the question of the size of gearing.

In some large power stations the hot air is taken to the stokeholds from the alternator, but the air ducts as a rule are costly and only in special conditions is such an arrangement permissible.

There have been difficulties with circulating currents through the rotor shafts and bearings; usually they can be overcome by insulating the end pedestal, as well as by the use of earthing brushes. Sometimes the parts of the turbine become magnetized in the course of manufacture, in which case it may be necessary to take steps to demagnetize them, but these precautions are very exceptional.

I notice that Mr. Juhlin in his curves deals only with electrical faults in the alternators. As a rule it is difficult to separate the electrical and mechanical faults, and there appears to me to be no necessity for providing the dividing line, as both are equally fatal.

Mr. Juhlin cannot understand why the ratio of the diameter of the rotor to its length is given consideration. He should remember that in carrying out pioneer work on the first large high-speed alternators consideration had to be given to every feature of the design which differed from previous practice. The length was one of the most important of such features and was the greatest departure from previous design, so that from the point of view of both electrical and mechanical requirements it had first consideration. Now that experience has shown that such long rotors are practicable, those who had not the anxiety of dealing with the original work have perhaps forgotten or are not even aware of the earlier perplexities. I would also refer to my reply to Major David and the conclusions arrived at. These conclusions were a result of many years' experience and of careful observations and calculations.

Mr. Juhlin appears to have some doubt as to the correctness of my conclusions upon the use of the helically stranded cable; I can assure him that the insulation difficulties which have been experienced are not confined to the stranded cable, but have been mainly with conductors made of rectangular strip using the hard insulation. I would refer him to my reply to Mr. Shepherd on page 467. That the ordinary conductor sub-divided into smaller sections and with the various sections transposed has disadvantages is proved by the fact that they have been replaced with stranded cable and with the flexible insulation. Other insulation besides the cotton covering has been used for the individual wires. I consider that the temperature of the conductors should be kept at a moderate figure, as the temperature which the varnish used to bind the mica flakes will stand has proved to be the limiting factor.

I have already dealt with the question of the stator slot design in reply to previous speakers. I am aware that heating has occurred, but these difficulties have been overcome. Their occurrence is not inherent in the tunnel-slot design.

Mr. Juhlin's experience in regard to the compounding of exciters and saturation gaps confirms my own.

## North-Eastern Centre, at Newcastle, 26 February, 1923.

**Mr. J. W. Jackson:** At present I fail to see the reason for the author showing such comparatively small machines in use at the early dates mentioned in his tables. I therefore wish to remind him that quite 23 years ago Messrs. Parsons built a 2 000 kW turbo-alternator for use on the North-East Coast; the fact that this machine is still in existence may be of interest. In 1903, machines of 5 000 kW built by that firm were also giving splendid service. One of these 5 000-kW machines has just recently been used for short-circuit tests on switchgear and it has been subjected to fully 400 short-circuits of varying degrees of intensity and still shows no signs of distress either mechanical or electrical. I am not at all sure that the author's remarks give sufficient prominence to the question of spacers for stator cores. A large number of machines have broken down due to the collapse or failure for other reasons of the spacer in the ventilating duct, and in many cases this trouble appears to have been due to insufficient weight having been applied when the core plates were being assembled, thus allowing movement of the spacer and so breakage, or even falling out, and quite a percentage of alternator breakdowns have been due to these spacers getting out of position, fouling the rotor and thus being forced through the insulation to the conductor. This is not by any means a new fault and very few of the manufacturers have been able to deal satisfactorily with it. The author touches lightly on the question of alternator ventilation. Very few quite appreciate what an enormous step forward has been taken by adopting the closed ventilation system, thereby allowing the same air to be used over and over again for the purpose of keeping down the alternator temperatures. Only when a little thought is given to the troubles due to ventilation by impure air and many makes of wet air-filters can the value of the closed system be appreciated, while the advance that has been made in the water cooling of the rotor as developed by Messrs. Parsons is an equally important step. When this question was first discussed all kinds of difficulties appeared to arise, and one very serious difficulty was that of securing a flow of water through the rotor cooling system when the turbine was running at high speed; a high pressure was superimposed on the water in the cooling ducts due to centrifugal force. These difficulties proved to be more apparent than real. There is, however, a point which must receive the closest consideration, namely, that the water used for this purpose must be rendered quite neutral, so that there may be no chance whatever of corrosion taking place inside the rotor cooling system. This point has of course been attended to, and it must not be lost sight of. The question raised by Dr. Thornton as to the way in which the field of the alternator should be quenched in the event of breakdown in the stator circuit, whereby he points out some of the dangers that exist through interrupting the field exciter circuit, is quite important. The exciter field and the main field circuits must be insulated to such a degree that they are capable of withstanding all the voltage reactions when sudden interruptions occur, because if the main field is not quenched in the least possible time, serious damage may be done to the stator core, thereby calling for an almost complete rebuild of the stator. The paper has been searched from end to end to see what the author has to say on the question of exciter commutation, this last appearing to be very much bound up in the general discussion on alternators. We have to confess that the author's firm, Messrs. Parsons, have met with some very special success on the question of high-speed commutation, but we have not yet seen any machines running at high speed that commutate so well and are so easily maintained as those built by Messrs. Vickers of Sheffield.

**Mr. H. Paterson:** In my opinion it is well that the difficulties which the designer has to face in connection with turbo-alternators should be brought to the notice of the purchaser. Referring to Figs. 2 and 4, which presumably have been inserted to show how much better Parsons alternators are than Metropolitan-Vickers machines, the curves hardly bear out this contention when analysed. The first point that strikes me is the difference in phraseology used in the two curves. Fig. 2 refers to the breakdowns on Parsons machines, whereas Fig. 4 refers to the faults on Metropolitan-Vickers machines. I think that everyone will agree that often a fault is eliminated before a breakdown occurs. Secondly, with regard to the number of machines, up to 1919 Messrs. Parsons appear to have installed only a few, and it is only to be expected that when dealing with machines of comparatively low speeds their percentage of failures would be less than that of the Metropolitan-Vickers Co. It will be noted that at the end of 1919 Messrs. Parsons had in operation slightly above 400 000 kVA, whereas the Metropolitan-Vickers Co. had just above 1 000 000 kVA in service. As the firm which I represent have always led the field in the question of speed, naturally in doing the pioneer work we experienced a few difficulties which have now been entirely overcome, and, furthermore, during the war period the materials, particularly insulation, were not so good as those obtainable to-day. It appears that although we have in service considerably more kVA than Messrs. Parsons the percentages of breakdowns at the end of 1922 do not differ materially. I am in entire agreement with the author on the point that high speeds have come to stay even on the larger units, and any little troubles which were experienced in the development are now being entirely eliminated. I note that the author puts forward a strong plea for the stranded conductor, and presumably this conductor is cotton-covered. Personally I have the feeling that cotton is not at all a satisfactory medium for turbo-alternators where the internal temperatures are certainly above that which cotton can safely withstand. Furthermore it appears likely that individual strands would vibrate, causing the cotton to wear in time. In my opinion, nothing but mica should be used for slot insulation, and this is a practice which the firm I represent have used for a number of years. The author also deals with the question of unequal expansion between copper and mica, and mentions that trouble has been experienced in this respect and that the only solution is the use of a flexible mica. As far as we are aware, we have had no trouble with the ordinary plain copper conductor, as the conductor can move slightly relatively to the mica insulation, the insulation being as hard as possible and with as large a percentage of pure mica as convenient. There is no doubt that this type of insulation has been used for many years and has proved entirely satisfactory, and it might be suggested that some of the troubles experienced by Messrs. Parsons are peculiar to the stranded cable, as the insulation is locked between the spaces of the individual conductors and on expansion the copper pulls the insulation. I am in complete agreement with the author regarding the closed system of air cooling, which has undoubtedly superseded both the dry and wet air-filters with their consequent disadvantages. As an illustration of the popularity of the closed system, I might mention that we have installed, or have under manufacture, well over half a million kVA of plant with this system of ventilation.

**Mr. J. H. Holmes :** There is practically nothing to criticize, as the paper describes difficulties overcome and problems solved in a thorough engineering manner. I should like, however, to draw attention to two small points. On page 439 reference is made in a footnote to Patent No. 14 723 of 1884 as relating to the first steam-turbine-driven dynamo. This patent is dated 7th November, but Sir Charles Parsons's earlier patent No. 6 734 of 1884, dated 23rd April, is really the first mention of such a machine, although in the provisional specification no details of construction are set forth excepting that the commutator is complete in itself and that it and the armature may be cooled by fluid circulating through the shaft or the casing round the armature. In the interval between the filing of the provisional and the complete specification, another patent, No. 14 723, was filed in which the details of the high-speed dynamo were set forth, and these details are described and illustrated in the complete specification of the earlier patent, although specifically disclaimed as part of that invention. It is because of these facts that I should like to see a reference to the earlier patent as well as No. 14 723, in the cause of historical accuracy. For the same reason I should like to draw attention to a statement on page 451 which says that the use of a liquid cooling agent was first applied to electrical machinery by Sir Charles Parsons in his original very high-speed dynamos built during the period 1884 to 1889. I do not think this claim could be substantiated, because there is no disputing the fact that some of the dynamos having Siemens shuttle-wound armatures constructed by the late Henry Wilde of Manchester were cooled by passing a stream of cold water through them. In the autumn of 1882 I was engaged in wiring and fitting up the showroom and offices of Messrs. Elkington & Co. of Birmingham with Siemens arc and Swan incandescent lamps and had the run of their works for some weeks, and I remember well seeing their large Wilde plating machine running and being cooled by a stream of water passing through it. I believe the water was passed through the hollow shaft, but sometimes it passed through holes in slabs of copper bolted between the poles of the magnet as distance pieces, and this construction is described by Comte Du Moncel in his book on the electric light published in 1880. May I remind members that it is to Sir Charles Parsons that we owe what is known as the " barrel " type of armature end winding which is shown I believe for the first time in the patent specifications to which I have referred.

**Mr. F. H. Downie** (*communicated*) : The method described of reducing the eddy-current losses in the stator copper is very good. I should like to know what percentage of the cable area is copper. In my opinion the author lays too much stress on the advantages of the tunnel slot in reducing flux pulsations on load. The bridge of the slot is highly saturated at full load, on account of the large number of ampere-conductors per slot, and the slot is therefore little better than a semi-open one. The ripples are absent on the voltage wave-form in the oscillograms taken on load, not because the slots are tunnel slots but because they are skewed one tooth-pitch. This construction would give the same results with semi-open slots. I am very much interested in the field-breaking tests described in the paper. I have been carrying out some tests on a small 4-pole, 30 kVA, 200 volt, three-phase alternator with a revolving armature. The machine has laminated salient poles. The results may be of interest to the author. The machine has a series winding on the poles, and this was short-circuited in some of the tests, thus forming a damping winding. The results are shown in Table B. From these results it is evident that a field-breaking switch with no discharge resistance will only reduce the flux quickly when the field circuit has no damping winding and the pole cores are not solid. When a single-phase short-circuit occurs, however, the potential difference across the rotor due to the pulsating flux produced by the pulsating stator magnetomotive force may reach very high values (compare tests 1 and 2). On the other hand, with the construction advocated by the author, namely the end caps well bonded to the rotor keys and body, the rotor is provided with a good damping winding. Tests 5 and 8 show that a rise still occurs in the potential difference across the field coils, but the flux, owing to the induced currents in the damping winding, takes nearly as long to die down to zero as it does when the field is broken with a discharge resistance in circuit. In the case of turbo-alternators with solid rotors, or with the end-caps bonded to the rotor keys and body, it does not seem to be of much advantage to break the rotor field current quickly when a single-phase short-circuit occurs. It does not reduce the stator current much more quickly and causes to be induced in the rotor winding a high E.M.F. which may damage the rotor insulation. This E.M.F. is due to the pulsation of the main flux produced by the pulsating M.M.F. of the stator windings.

TABLE B.

| Test | Exciting voltage | Field discharge resistance used | Maximum P.D. on field when breaking | Machine short-circuited | Time for flux to die down to zero | Series coil short-circuited |
|---|---|---|---|---|---|---|
| | | | volts | | seconds | |
| 1 | 40 | No | 580 | No | — | No |
| 2 | 40 | No | 1 614 | Yes | 0·36 | No |
| 3 | 40 | Yes | 40 | Yes | 1·2 | No |
| 4 | 40 | No | 320 | No | — | Yes |
| 5 | 40 | No | 440 | Yes | 0·95 | Yes |
| 6 | 40 | Yes | 40 | Yes | 1·2 | Yes |
| 7 | 100 | No | 450 | No | — | Yes |
| 8 | 100 | No | 650 | Yes | 1·0 | Yes |
| 9 | 100 | Yes | 100 | Yes | 1·1 | Yes |

**Mr. J. Rosen** (*in reply*) : Mr. Jackson's views agree on the whole with my own and do not call for comment.

In reply to Mr. Paterson, the curves in Figs. 2 and 3 are given to show the reliability of high-speed alternators built in this country, and I had no intention of making invidious comparisons. His other questions have been raised also by his colleagues, and I would refer him to my replies to them.

I am indebted to Mr. Holmes for his corrections. The patent number has been added in the paper as published in the *Journal.*

In reply to Mr. Downie, the percentage of copper in the cable area varies according to the diameter of wire employed, and to the formation of these wires in the conductor. Mr. Downie's experiments on a small machine are interesting, but the results do not agree with those of recent tests on a 3 750 kVA machine (see Table A, page 873). These results show clearly that the flux in the turbo-alternator dies away more rapidly without a discharge resistance than with a discharge resistance. I agree with him that the rate of reduction of flux is higher without a damping circuit.

## NORTH-WESTERN CENTRE, AT MANCHESTER, 6 MARCH, 1923.

**Professor G. Stoney :** In my early days I was closely connected with the design of turbo-alternators. When I went to Messrs. Parsons in 1888 the largest was a 75 kW, single-phase, 80 period, 1 000 volt machine. As the work of the firm increased I had not so much to do with the electrical side but applied myself more directly to the turbine side ; I think, however, I may claim to have assisted in the design of many direct-current high-speed dynamos, and of all abominable things large high-speed dynamos are about the worst. Fortunately, Sir Charles Parsons, by the introduction of gearing, has got rid of them. The paper is of very great interest to me as showing the advance that has been made during the past few years, more especially since I left Messrs. Parsons about 11 years ago.

**Mr. G. A. Juhlin :** The author states that the system shown in Fig. 16 is unique ; it may be of interest to note that practically the same system of ventilation was adopted for a 1 000 kW machine built in 1911. Fig. K shows this system of ventilation. Substantially the same type of ventilation is used to-day with the large turbo-alternators manufactured by the company with which I am associated, with excellent results. In connection with ventilation, the author deals with the closed air-circuit system ; I think it should be realized that while this system is quite an old one, it is only recently that the type of cooler now in use has been developed. As far back as 1916, however, the French Westinghouse Company had in operation a cooler, which was of the finned type, on a 4 000 kW machine. As far as I am aware, coolers in use on electrical plant up to that time had been of the ordinary plain-tube type. A long series of investigations was undertaken by the Metropolitan-Vickers Electrical Company in order to determine the heat transmission of the finned type of cooler, and a highly efficient cooler was developed as the result. The investigations were undertaken through the information received regarding the successful operation of this type of cooler in France. Up to the present time 62 coolers are installed or under construction, corresponding to an alternator output of 575 000 kW. I am of the opinion that the closed air-circuit system of ventilation is a great advance on the old systems of air filters which had to be employed in an endeavour to keep a reasonably clean atmosphere. The closed air-circuit has a considerable advantage as there is not sufficient oxygen available in the air contained in the system to support combustion, which has always been a source of trouble due to the fact that a very minor fault would completely destroy the windings by fire. On this score alone I consider the closed air-circuit system to be justified. The author deals with the difficulties experienced with rotor-retaining rings, due to the breakage of the lip on such rings. We have experienced similar troubles and have carried out extensive researches to determine the cause, which at first was taken to be due to the heavy currents flowing in the rotor under short-circuit conditions. Subsequent investigation, however, showed clearly that while the arcing set up due to the short-circuit current might be a contributory cause, it was not the main one, as in some instances troubles with lips have been experienced without any accompanying arcing. The conclusion arrived at was that the cause of this trouble was a mechanical one due to deflection of the shaft. In the rotors with which trouble has been experienced, the retaining ring was supported from the shaft by means of an end disc, so that any movement of the shaft was transmitted through this end ring to the retaining ring and so to the point of support at the end of the rotor. To overcome this trouble a special construction has been developed, and Fig. L shows this latest type of construction. It will be noted that the rotor ring is supported from a ring which is independent of the shaft and forms a portion of the rotor body itself. The result of such an arrangement is that no movement caused by shaft deflection can be transmitted to the retaining ring, which therefore remains entirely undisturbed. With regard to the question of the bonding strips between the rotor wedges and the rotor-retaining rings, while these are undoubtedly an advance on the old type where no bonding strips were used, I do not think the author has gone far enough in this connection. I consider that the correct solution of this difficulty is to provide a complete damper with the short-circuiting ring, so that it is not necessary to transmit the current from the wedges into the rotor end cap. Such an arrangement has been developed and tested, with eminently satisfactory results.

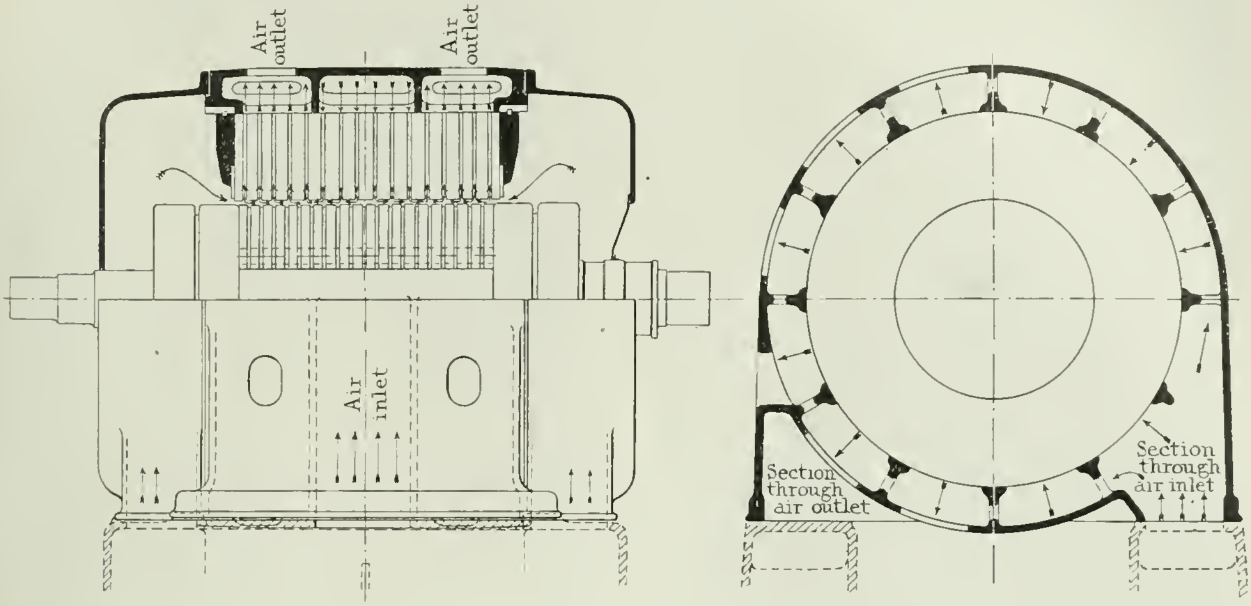


Fig. K.

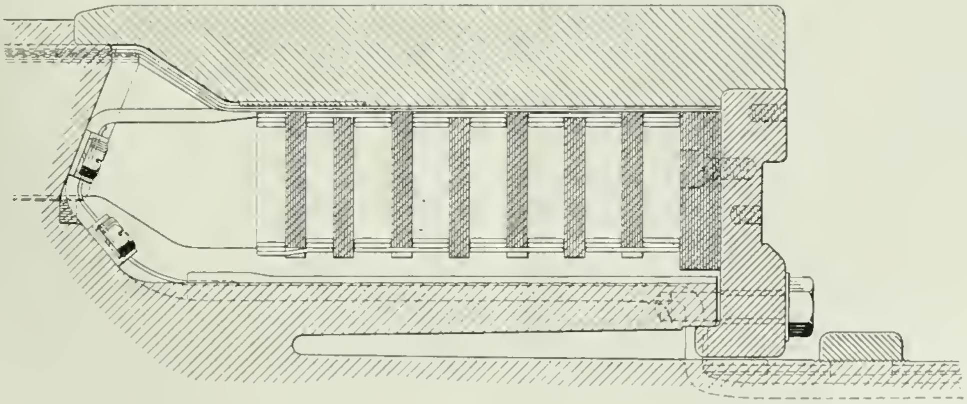


Fig. L.

**Mr. H. C. Lamb**: The paper is equally interesting to the operator and the designer of plant. The list of alternators for 3 000 r.p.m. actually running and now under construction is rather a remarkable one. Fig. 2 showing the breakdowns is particularly interesting. For the past three years the breakdowns amount to only 1 per cent per annum. I think that those figures ought to be brought home to the insurance companies who insure turbo-alternators. They mean that in a station with, say, five alternators, a breakdown is to be expected once in 20 years, though the author would probably stipulate that to get such a result the alternators would have to be made at the Heaton works. The point I wish to make is this. The rates of insurance to-day vary, according to the reputation of the maker and the record of the station, from 3 to 6 per cent per annum of the total value of the alternator. As Fig. 2 shows failures of only 1 per cent (and no doubt many of those failures were comparatively inexpensive to repair), it does appear that we should be able to effect insurance at a very low rate indeed. Of course one cannot compare very well the results obtained on a small number of alternators with those which the author gives for, I think, over 200, but I have found it of interest to prepare a record of 11 turbo-alternators over a period of 10 years. During the whole of that time the stator breakdowns, which are what Fig. 2 deals with, were four, that is a rate of 5 per cent per annum. Of these, three were not fairly chargeable to the alternator itself, because they were the results of quite external causes, such as carrying over water from a wet filter which was not in working order—a condition for which the alternators were never designed. Only one breakdown was really due to an inherent failure of the alternator itself. The author shows a closed air system which certainly seems likely to reduce very much the number of high-tension alternator troubles. The Manchester set illustrated on the lantern slide was examined a few weeks ago and found to be just as clean as when started up a year previously. The author says that rotor failures are few and easily remedied, but I do not agree with him. At any rate this has not been our experience, because rotor failures have been just double the number of stator failures. During a 10-year period they have occurred at the rate of 10 per cent per annum. Only one of the faults was due to a mechanical cause. That was the fracture of a bronze end ring which took place when the alternator was running up, and in this case it was extremely fortunate that very little damage was done; if the accident had happened when the plant was running at full speed a complete wreck would probably have been the result. Of seven rotor electrical breakdowns two were due to failures of slot insulation. It does appear that, because a rotor is run at low voltage, insufficient care is taken to put in really sound insulation. The most interesting of these cases was a heavy rotor, weight 55 tons, with a core 11 ft. long. The trouble was caused by bonding strips (such as those to which the author refers) between the slot wedges and the end bells. These strips were in two pieces, and when the wedge, on being driven up, reached the second piece, the end was fouled and turned over. Evidently the man did not notice this and drove the wedge home. The alternator ran for five years before breaking down at that spot, and then had to run another year before the repair could be made. The paper refers to the instability of exciters. Certainly the compound-wound exciter is very much better than the shunt exciter, but I have come across only one case of trouble with a shunt exciter. On that occasion a commutator was being wiped with a greasy rag when the exciter was on light load with a good deal of resistance in the field. The exciter lost its field, but nothing particular happened. It was noticed that the main field had gone; this was rectified in a few minutes, and the alternator continued running as before. The author does not approve of the series regulator. I think this is really put in not for the purpose of regulating when the plant is working in conjunction with the exciter, but as a stand-by to the exciter so that a supply can be given from a separate source. It does not seem wise to run the risk of having a very large plant out of commission because of a failure with a small exciter, and series regulators have on several occasions proved useful in this way. On page 458 reference is made to field-discharge switches. It is not quite clear whether the author is in favour of doing away entirely with the field-discharge resistance or not, and I should like to mention a particular case. The trouble began when a steel wedge was driven through a high-tension cable a mile away from the generating station. That caused a very bad short-circuit and the pressure-rise which followed broke down one of the alternators, an arc starting through one of the mica tubes on to the core. The effects of this arc were carried through to the end turns. There were the usual flames and smoke coming from the air inside, and the oil switch and the field-discharge switch opened automatically. The air dampers were closed and the machine was shut down, but, on opening up immediately it had stopped, there was no sign of fire inside the case. At a casual glance it would hardly have been noticed that there was anything wrong, except at the two places where the arcs had occurred. Of course the core was damaged at one spot, but the point I wish to put to the author is this: The field-discharge resistance had a value $1\frac{1}{2}$ times the resistance of the rotor windings. Does the author consider that, if there had been no field-discharge resistance and the field had consequently shut down more quickly, the damage to the core would have been substantially less?

**Mr. G. F. Sills:** With reference to the table showing progress in sizes and speeds, while I was in Canada a well-known town there in 1913 wished to purchase a 3 000 kW turbo-alternator set, at 60 periods and 3 600 r.p.m. The speed of the alternator appeared to be the stumbling block for this size so far as the British manufacturers were concerned, so the alternator was made abroad and the steam turbine in this country. Referring again to Table 1, I believe I am correct in saying that the first 6 000 kVA, 3 000 r.p.m. set was put into commission in this country in 1917 at Wolverhampton, where it has since given every satisfaction. With reference to the author's remarks on the question of stranded cable, at least one British cable maker has made sector-shaped cables on these lines for many years, the only difference being that there is no insulation between turns. Apparently the company in question do it in rather a different way from the author, because they build the cable strands up of, say, four or five different diameters of wire which are so placed that as they go through the die they automatically take up the correct position in the cable and are not crushed in any way; in fact, examination of the cable strand after it has been through the machine shows that the wires are perfectly round. Stranded cable as described by the author does not give a good space factor. To reduce the eddy currents the same result as the author's could be obtained with solid copper (in comparatively small sections, however, with mica between) by making the connections at one end of the stator in such a way that the laminations forming the conductor are transposed. The splitting of the conductor into three parts, shown in Fig. 11, is claimed as an advantage. Is not this rather offset by the fact that it is hardly possible to mould mica on to the bars when they deviate from a straight line, and that it is necessary to seal three joints at the end of every conductor at both ends of the machine? Again, would not this arrangement cut down the creeping surface? Fig. 16 shows the author's method of ventilating large turbo-alternators. I note that it is claimed as a patent. I am at a loss to see where the patent comes in, as there is no patent in deflecting the air to the right or to the left as the case may be. A somewhat similar form of ventilation was used as long ago as 1907 for some 7 000-kVA alternators, that is, so far as it applies to exhaust and inlet ventilating chambers, but in these cases the air was carried round partly circumferentially. There is no reason why external forced ventilation should not be used on these large machines. In the case of a modern 16 000 kVA, 3 000 r.p.m. turbo-alternator a double system of ventilation is used, i.e. at each end of the rotor there are two double fans. These draw air through and ventilate about a quarter of the stator. The middle half of the stator is ventilated from an external motor-driven fan. I was in a station some time ago where an alternator was ventilated by an external fan, and although the alternator was not running I noticed that the fan motor in the basement was rotating. It appeared that the updraught from the stator frame was sufficient to rotate the motor and fan. In this case, however, the actual reason why the motor rotated, although there was no current on it, was that it was fitted with ball bearings. I do not think that there is much doubt that the enclosed type of filter has come to stay. This system should certainly prolong the life of an alternator and keep its temperature relatively the same after several years' use. Several manufacturers now make these filters, incorporating the necessary automatic safety devices. Wet filters have given good service but must be used carefully. I know of some 6 000-kVA sets where the "Megger" readings have never fallen below 40, although using wet air-filters. Naturally, however, the closed system will give cleaner air and a much larger margin of safety. I believe that the closed air-system cooler costs about 50 per cent more on the smaller sizes, but personally I think that it is worth 100 per cent more. With reference to the water-cooled rotor shown in Fig. 19, apparently the holes have been taken out of the rotor just underneath the rotor slots. I believe I am correct in stating that the greatest strain occurs thereabouts. Does the author approve of this for a 12 000 kW, 3 000 r.p.m. set? From the last paragraph but one in col. 1 on page 452, it rather looks as if this method of cooling were not really capable of absorbing much heat. Personally, I should prefer a rotor with a 70 degrees C. rise to water cooling. The author refers to the introduction of saturation gaps in connection with the exciters. I have knowledge of two exciters, each of 96 kW for 18 750-kVA turbo-alternators, having windings to compensate for armature reaction. It was found that the exciters were quite stable at 114 amperes, 2 volts, and at any voltage between 2 and 240. These exciters do not require a series regulator, which is an advantage for the reasons given in the paper. Referring to the author's oscillograph tests, I have recently seen records of similar tests carried out by another manufacturer, and these confirm his conclusions. As regards arcing and breaking of end bells, I made inquiries from two designers whose firm have built about a million horsepower of turbo sets. While one works has had no trouble the other has very occasionally had signs of pitting, but this has been attributable to the fact that insufficient shrinkage allowance had been made for the end bell on to the rotor. Neither of the works has seen signs of the cracking mentioned by the author, and it would probably be found that where cracking has taken place the end bells are not strong enough. Provided the correct shrinkage allowance is obtained, there is apparently no advantage in spigoting the end bells as shown in Fig. 26, as compared with Fig. 27, particularly when it is remembered that the end-bell steel is, say, 20 per cent stronger than the rotor steel. I should like the author to state why the rotor keys are serrated as shown in Fig. 25. One large firm find it preferable to use a number of short keys about 9 in. long, as a much better fit can be made in this way than by using one long key. With reference to the author's remarks on the question of copper bonding under the end bells, is there not a possibility that oxidation would take place and cause bad contact in time? It was interesting to read of the numerous short-circuit tests carried out on two machines, but it is probable that the buyers of these particular machines would not have been pleased if they had known of all these tests. In this connection, in an advertisement in regard to the rupturing capacity of some switchgear it was claimed that a 4 000 kVA alternator gave a short-circuit equivalent to 138 000 kVA; apparently a unique machine. It is interesting to know that one firm in connection with a 16 000 kVA, 3 000 r.p.m. turbo-alternator, in addition to dovetailing the teeth of the stator laminations into the stator, place bolts through the core as near to the bore as possible, in order to prevent laminations from becoming slack at the teeth. These bolts are insulated throughout and lie on a circle of rather larger diameter than the roots of the teeth. It should be noted that there are only a few bolts which are made of bronze and insulated throughout; in addition small brackets are provided, secured to the stator frame and arranged in such a way that they will prevent any vibration of the bolts in service. It is possible to tighten up the brackets while the machine is in service, as small hand-holes are provided for this purpose in the stator frame. On machines of the very large type referred to, having only two poles, the flux per pole is so large that a very deep core is necessary, and these few additional bolts then become essential. I should be glad if the author would give his views on 11 000- and 12 000-volt machines. Attention is drawn to the necessity of carefully building the core on these very big machines. In one works with which I am acquainted every stator lamination is ground on one side so as to remove the burrs left after punching.

**Dr. S. F. Barclay:** The author has dealt with a very wide subject, and it was impossible within the scope of a single paper for him to consider exhaustively the many interesting points raised. For example, in dealing with the history of turbo-alternators the only reference made to a somewhat important local firm, who have done a fair amount of work in the development of turbo-alternators, consists of the figures of their contribution to breakdowns. It must be of great value to users for manufacturers to publish statistics of the breakdowns of turbo-alternators, and the author is to be congratulated on following the lead given by another manufacturer in this country about two years ago. I would point out, however, that statistics, as applied to the breakdown of turbo-alternators, can be very misleading. There are in commission at the present time many alternators which, from the point of view of size and voltage, should be almost as dependable as low-speed machines, and, on the other hand, there are some machines of extra high voltage and some for unusually large outputs, which, to some extent, must be regarded as being in the experimental stage. It is not very informative to give simply the number of breakdowns without indicating their nature. The value of the figures is, moreover, reduced by giving only the stator breakdowns; why the rotor breakdowns should be excluded I cannot imagine, as, on the whole, they must be more numerous than the stator breakdowns. The author refers to a case in which the mica tubes of the stator conductors were eroded by grit, and he places such a happening in the class beyond the control of power station engineers and manufacturers. It should be pointed out that if the air had been effectively filtered such a thing could not have happened, and air filtration is well within the control of the authorities concerned. The author speaks about adopting "the very conservative and safe figure of 300 ft. per second" for the peripheral speed, and connects his statement with running speeds of from 1 000 to 3 000 r.p.m. To present the case in this way is a little illogical, as the centrifugal force of unit mass at the periphery would be three times as great in the case of the 3 000 r.p.m. machine as in the case of the 1 000 r.p.m. machine. As the author is well aware, there are, however, other limits that have to be taken into account besides the peripheral speed; the rubbing speed in the bearing is one, and the stress in the neck of the journal is the other. The adoption of a "conservative" value for one of these three limiting factors may lead to an unduly high value for one of the other two, and the best way to approach the matter would be to strike the best balance between the three and not to approach the problem with the bias that one has to receive preferential treatment. The author makes the following very remarkable statement with regard to the rotor end caps: "Moreover, it is possible to deform a cap 25 in. diameter, 1 in. thick, by as much as $\frac{1}{8}$ in. on the diameter during its assembly over the windings." What is happening to the windings whilst a very strong cap is being deformed in this way? The determination of the eccentricity of the end cap whilst running is very interesting, and the author, or whoever is responsible, is to be congratulated upon the very ingenious method employed. I suggest, however, that it would be desirable to modify the words "Photographing the length of an electric spark jumping across the gap between a fixed contact and the cap." What actually is photographed is the fixed contact and the cap, and the spark provides the necessary illumination. I am surprised that the author is able to measure the gap to within 0·01 in. Has he ever satisfied himself by exact tests that the stranded conductor does really effectively reduce the eddy currents, as compared with the laminated conductor? My own experience is that the stranded conductor fails by a very long way to do all that is claimed for it. The stray loss can be kept down to a reasonably low value if the solid conductor is properly laminated, and, if it is of unusual depth, parallel circuits should be arranged joined together only at the machine terminals. The paper refers to the vibration of plates and core-plates; the vibration of tooth supports involves design and it is surely better practice to form them by machining out of a solid ring than to use loose fingers as the author does. If a core vibrates, most probably insufficient pressure has been used in the building, but care must be taken not to use excessive pressure which may lead to undue core loss. The author quite rightly refers to the danger with the wet air-filter of free moisture being carried over into the alternator and collecting on the windings. It should be pointed out, however, that if the air filter is properly arranged and in correct adjustment no free moisture can be carried over. With the spray type of filter I have found that much of the trouble with the carrying-over of moisture arises from corrosion of the eliminator plates. In a filter of this kind the water is used over and over again, and in an industrial centre sufficient sulphur may be removed from the air in the course of a few days to give the water a decidedly acid reaction and to cause the metal plates to be attacked rapidly. In such situations it is a very desirable safeguard to add a little alkali to the water to neutralize the acid as it is formed. Undoubtedly, however, the ideal arrangement is the closed system of ventilation, but it has the disadvantage of being more expensive and more difficult to accommodate, and in some cases there is difficulty in providing the necessary cooling medium. The paper refers to the question of the instability of exciters; since it deals to some extent with the history of the subject the reference is appropriate, but to-day there is no excuse for any manufacturer building an unstable exciter. The damage done to rotor end caps, ascribed by the author to heating due to the flow of a heavy current along the surface of the rotor, is very interesting, but I feel very doubtful whether heating really was the cause of the cracks in the steel. To me it seems quite unsound mechanically to attempt to prevent the end cap opening elastically by registering the end under an overhanging lip machined at the end of the rotor. The end cap cannot carry the load due to the centrifugal force of the end connections unless it is free to open elastically, and in point of fact the author ascertained that at one part of the rotor a cap opened about 0·01 in., and at another part approximately double that amount. For such a happening to be possible the overhanging lip on the rotor must be overstressed. It is an axiom of the design of any structure that no part can carry a load except in so far as it is free to yield elastically, and it is entirely unsound to attempt to prevent the elastic movement of one part by another part which has insufficient strength for the purpose. From the figures given, the author must use nickel-chrome steel for his caps, and I would draw his attention to the great importance of verifying that the steel is in a correct state of heat treatment. Nickel-chrome steel is much less easy to handle than plain carbon steel and possesses its excellent characteristics only when made under the best conditions, and correctly oil-hardened and tempered. There is such a good chance of the phenomenon of "temper brittleness" that I should not apply nickel-chrome steel to any such important duty as that of an end cap, unless the impact test were added to the usual tests.

**Mr. J. A. Kuyser:** On a number of points the conclusions and the recommendations given in the paper do not agree with my experience. First, as regards ventilation, the system described is very efficient with the exception of the ventilation of the stator end connections. The end compartments draw a comparatively small quantity of air from the stator casing, and this air will already have attained a certain temperature before it strikes the stator end connections. In the usual systems of ventilation cold air is drawn directly from the air ducts in large quantities. The author mentions cases of trouble due to overheating of stator end connections. These were perhaps due to insufficient ventilation. The system described has already been used either in practically the same form, or in a slightly different form by the following firms: Westinghouse Co. (U.S.A.), British Westinghouse Co., General Electric Co. (U.S.A.), etc., and it appears doubtful whether the patent can be upheld. As regards the design of very long machines, it may be of interest to give the main dimensions of some generators built by the Westinghouse Co. (U.S.A.) about 1910. These machines had rotor diameters of $23\frac{1}{2}$ in. and a core length of 80 in., the ratio being similar to the figures given in the paper. In connection with the automatic field switch, the author has adopted the recommendation given in my recent paper to omit the discharge resistance. I do not agree with the conclusion reached, that the eddy currents in the rotor body are more severe in the case of the rotor circuit being opened than in the case of a short-circuit on the stator. An oscillograph across the slip-rings under the two conditions indicates that the reverse is the case. In connection with armature windings, I am surprised that the author takes up the position that movements of the winding cannot be prevented and that it is therefore advisable to use flexible insulation. As far as the end connections are concerned, small movements may take place, but these are very small and have no harmful effect whatever, since the insulation of the end connectors is always of a flexible nature, being applied in the form of tape. As regards the slot conductors the position is different, and it is possible to prevent movements of these; it is therefore undesirable to use an inferior grade of insulation to obtain flexibility. The objections to flexible insulation containing a high percentage of fibrous material are as follows: It is difficult to ensure that the conductors remain tight in the slot at the comparatively high temperatures inside the stator. If the conductors become loose, vibrations may destroy the insulation. As regards the use of flexible cable, several firms, including that with which I am associated, have had unfortunate experience with this type of conductor, and its use was discontinued some years ago. The author mentions trouble caused by cracking of the insulation due to expansion. This trouble has never been experienced on machines wound with straight bars, and the reason is probably that the individual wires of the cable are buried in the insulating tube and relative movements are prevented. In the bar-type winding each strap is taped with mica tape which provides a sliding surface and allows different expansion of mica tube and copper bars.

**Mr. D. S. Paxton:** The author exhibited a lantern slide indicating the sand-blast action of grit in the interior of a turbo-alternator. This is, I think, a very eloquent testimony to the necessity of installing some form of filter, or otherwise preventing grit entering a machine. There are still engineers who consider a filter unnecessary and believe that sufficient protection is afforded by a wire-gauze screen at the air-duct inlet. The photograph shown on the slide is a clear proof of the fallacy of this view. Everybody agrees that the closed air system is a good thing when it can be applied, but it cannot be applied in every case. In stations using cooling towers it is inadvisable to attempt to cool all the alternators on the closed air system. In such cases it is the usual practice to use the boiler make-up water for circulating in the air coolers and, though this will suffice to cool the circulating air in a portion of the generating plant, the volume of make-up water will be found insufficient to provide circulating water for alternator closed-circuit coolers for the whole output of the station. In such cases, therefore, and in other cases for other reasons, the closed air system is not always applicable, and reference may be made to a system of air filtration that is not mentioned in the paper, but which overcomes the defects referred to in the paper as associated with dry and wet air-filters. I refer to the Visco oil-film type of filter, which on the Continent has come into very general use. During the past five years something over 3 million kW of plant has been equipped with this type of filter. In this country there has not been quite the same growth because the system was not introduced until a considerably later date; but during the past year the Visco filter has been adopted for some 50 or 60 machines and has invariably proved satisfactory in operation. In considering the question of alternator cooling, therefore, this system should be borne in mind as an alternative method of dealing with the question of maintaining the air supply clean where the closed air system is not applicable.

**Mr. L. W. Schuster**: Papers from leading designers are most enlightening and welcome because their experience with plant troubles far exceeds that of users whose experience, however wide, must of necessity be of a comparatively limited nature. Though the company with which I am associated has had unfortunate experiences with most, if not all, the troubles recorded in the paper, the manufacturers have in each case the full knowledge of the causes leading to them and the remedies adopted. The two lowest curves in Fig. 2 are not quite clear to me. The bottom curve gives the annual number of stator breakdowns and, if my interpretation is correct, the curve above this represents the annual number of breakdowns of every kind. I shall be glad if the author will explain how it is that the figures representing the latter are exceeded by the former previous to the year 1916, as it appears that the part is greater than the whole for the earlier period. Again, I do not follow the relationship between the curves. Take the year 1921. Apparently the number of alternators installed was 200, and the number of breakdowns about 30, or 15 per cent. The percentage curve shows this latter figure as 1 per cent and the text confirms this value. As these curves will naturally include the smaller machines with which more experience has been gained, it would be interesting if a differentiation were made between these and the larger machines which during the last few years have been in the experimental stage. I should be glad, therefore, if the author in his reply would furnish figures grouping the sets into two classes, say, above and below 5 000 kVA. On page 441 it is stated that the largest machine installed in America is of 9 375 kVA capacity. Surely this is a misprint. On page 446 the presence of residual oils is advocated in order to obtain flexibility of stator insulating tubes. My company has had adverse experiences from the splitting of insulating tubes in the manner described, but it does not seem to me that the remedy named is the final solution of the difficulty. It appears that with the development of these mammoth sets one of the first ideals to be aimed at is a fire-proof machine. During the last year or so several cases of fire have come directly under my notice and it has struck me what a vast amount of damage can be incurred in the space of only a few seconds. If the insulation of a machine is pierced and arcing takes place, it seems that there is always the liability of a machine catching fire and the flame at once licking round the whole periphery, due to the presence of volatile oils and varnishes. This means the destruction of the whole of the windings and possibly the cracking of the stator frame in addition to the other damage. Thus in the course of a few moments damage may be sustained to the value of £10 000. Similar remarks apply to the use of a bituminous compound between the tubes and the slots. It appears that designers are compelled at present to use materials that are not pre-eminently suitable, but with the evolution of large turbo-alternators they will be forced to develop some form of fire-proof construction. On page 452 is described an 18 000 kVA alternator, the stator core of which has an internal diameter of 35 in. The rotor is said to have a peripheral speed of 345 ft. per second, which is equivalent to a diameter of 33 in. As this implies a 1 in. air-gap I should like to ask if these figures are correct. From page 453 it appears that the author is in favour of eliminating the main field regulator for the sake of simplifying the plant, but, in view of the greater length of time required to destroy the main field in case of emergency, it appears (from page 458) that the author is really in favour of retaining it. I believe that its retention was also advocated by Mr. Kuyser in his recent paper.

**Mr. A. B. Mallinson**: Several speakers have mentioned the advantages of the closed air circuit, and I think that the remarks of the last speaker tend to emphasize that point. Surely it is impossible for a fire to take place in a closed air circuit. There is only a limited amount of air in circulation, and, if a fire is started through any electrical cause, the oxygen in that closed air circuit will soon be exhausted and the fire obviously must go out. The insurance companies should give a special rebate for machines with closed air-circuit cooling systems.

**Mr. J. Rosen** (*in reply*): I am in agreement with Professor Stoney as to the difficulties inherent in the design of large high-speed d.c. dynamos, and I agree also that gearing has eliminated these difficulties.

In reply to Mr. Juhlin, I have already dealt with the closed-circuit system of ventilation. The scheme of alternator ventilation described in the paper, with several air pressure and exhaust compartments placed alternately throughout the length of the machine, has many advantages, especially with regard to the length, enabling very long machines to be built. Mr. Sills also mentions the method of ventilation by means of circumferential air-flow. I have used this design in the past on several large alternators, but have found that the later design, using axial flow, is more effective for cooling the alternator, more especially at the centre. Mr. Juhlin, in spite of his statement to the contrary, appears still to agree with me that the faults which he has experienced are, in part at any rate, due to the circulating currents, as he proposes to use a massive damping winding on the rotor. In the design illustrated in Fig. 26 a suitable radial clearance is provided between the faucet on the rotor body and the spigot on the cap. This clearance is sufficient to allow for full expansion of the caps due to heating and mechanical loading, and there is no necessity therefore for the complicated machining of the shaft shown in Fig. L. The latter arrangement is ingenious, but it has the disadvantage that it weakens the shaft end.

Mr. Lamb has opened out a new aspect on the use of the closed-circuit system of ventilation, i.e. the question of insurance. This is most important, and the information which he gives is very valuable.

Mr. Mallinson has also made reference to the fact that the oxygen in the closed-circuit system is soon exhausted. For example, in a 10 000 kVA alternator installation, as mentioned on page 471, there is only sufficient air to burn completely 1 lb. of wood, from which it will be seen that in the event of a fault the damage would be confined to the point of failure only and that any damage due to fire would be negligible.

The rates of insurance given by Mr. Lamb appear to me to be high, and, in my opinion, with the improved reliability of alternators there is no reason at all why the insurance companies should not reduce the rates, or why a special abatement for alternators fitted with the closed-circuit system of ventilation should not be made, just as abatements are provided for buildings in which special precautions are taken to prevent fire or to limit the damage in case of an outbreak.

I have had one experience only of a fault on an alternator fitted with a cooler. The damage was localized to the point of breakdown, and there was no sign of damage due to fire. The core was cleaned, and the two stator conductors affected were replaced in a very short time.

I am interested in Mr. Lamb's description of the rotor fault, and to hear that he has had more difficulties with rotors than with stators.

A main field regulator would be of service as a stand-by to the exciter for separate excitation. My objection to its regular use, apart from the energy absorbed, is that it takes up a large amount of space in the station, and the temperatures round the regulators are uncomfortably high. Long lengths of large-section cable would also be necessary. An alternative to the main field regulator would be either a spare exciter armature or a complete spare exciter—which latter would be an equally or more satisfactory solution of the difficulty. I think that manufacturers are fully aware of the possible weaknesses in exciters and take every precaution against failure. The main field switch without discharge resistance would be operated in an emergency such as that described by Mr. Lamb. I have referred to this in reply to Mr. Selvey on page 466. Table A on page 873 shows the time taken for the voltage to fall with different switches, from which it will be seen that on opening the field the voltage falls to 51 per cent of its original value in 0·8 sec. without discharge resistance, and only to 80 per cent in the same period with a discharge resistance approximately equal to the rotor resistance. In the particular example quoted by Mr. Lamb it is difficult to give an opinion on the exact extent of possible damage without having made a personal examination and being acquainted with all the circumstances. I think he will agree that the damage in the stator under the conditions mentioned will be appreciably less in the absence of the field discharge resistance.

In reply to Mr. Kuyser and Mr. Sills, I would again state that the cable used for the stator conductors is of peculiar design, and that the individual wires are helically stranded. I am aware that some cables are made with parallel strands, but there is nothing to be gained by the use of such cable in alternator construction. The stranded cable of which Mr. Kuyser has had experience has not been of the Parsons type, which is covered by patents.

In reply to Mr. Sills, alternators of 25 000 kVA at 3 000 r.p.m. are being built without water cooling. I would remaind him that if the space at the bottom of the slot in the design illustrated were not filled with the cooling-water tube it would probably be occupied by copper. The damping bars or bonding strips have been used for several years, and no difficulties due to oxidation have been experienced. I have dealt with the other questions in my earlier replies.

In reply to Dr. Barclay, my object in publishing the record of failures of alternators was to show that in spite of the increase in rating and speed of the modern machines, their reliability—as measured by the decline of the breakdown curves—has even been improved over previous performances with the older and smaller machines. I had compiled details of the faults, but to publish a complete record and description would have occupied much space and would have had no real value. Dr. Barclay suggests that the erosion of the stator conductor bars might have been prevented. I would mention that, owing to the war conditions, filters were late in delivery and only a temporary dry air-filter could be installed. A good deal of work which was not under the supervision of the station engineers was in progress outside, and there was at the time perhaps some excuse for their not having prevented the grit entering the alternator air ducts. Dr. Barclay considers that to take the same maximum peripheral speed for all speeds of rotation is illogical. Other speakers have also made a similar statement, and have fallen into the same error. I think that Dr. Barclay has failed to distinguish between the centrifugal force per unit mass and the force per unit area (stress in lb./sq. in.)—these values are of entirely different dimensions.

In the description of the experiment on the distortion of the rotor end cap, I agree that it would perhaps have been more correct to have mentioned that the distance between the outlines of the electrodes was measured, and not the length of the spark, which was, of course, very irregular.

On the question of the helically stranded cable, I can assure Dr. Barclay that excellent results are obtained, and I would refer him to my replies to other speakers.

The ends of the stator core are supported with a massive cast-iron ring, which carries the supports for the teeth between the conductors.

The significance of "temper brittleness" in nickel-chrome steel is a matter of controversy; it is a well-known fact that important parts of aeroplane engines during the war were made by one firm of this material in a temper-brittle condition, and gave entirely satisfactory service. The same material when used in rotor end caps has given good results.

I would refer Mr. Kuyser to my replies to Mr. Juhlin and Mr. Sills. In regard to the question of the difference between the voltages induced in the rotor on short-circuit and on the field breaking, he must remember that the type of switch used in breaking the main field circuit affects the induced voltage, and therefore the currents induced in the rotor. If a quick-break switch is used in the field the conditions are very much more severe than on sudden short-circuit. Why he considers the flexible insulation to be inferior I do not know, as it has given results equally as satisfactory as, and in my own experience more satisfactory than, the hard grade of insulation. I agree with him that it is difficult with hard insulation to ensure that the conductors are tight in the slots. For this reason, straight bars of other manufacture have been replaced by the helically stranded cable and flexible insulation.

Mr. Kuyser suggests that it is possible to prevent movement of the slot conductors; differential expansion between the copper conductors and the core, due to temperature differences and unequal coefficients of dilatation, cannot be prevented. For this reason, there should be some "give" in the insulation, and the hard variety does not allow of this. The troubles experienced have been principally with the bar winding and not with the stranded cable construction.

I must thank Mr. Schuster for raising the question with regard to the lower curves in Fig. 2. Unfortunately, an error was made in plotting the "yearly fault" curve; it is actually drawn to twice the scale of the "total fault" curve. This information will, I hope, remove the difficulty, and enable him to follow the figures. Mr. Schuster has confused the main field regulator with the main field switch.

I have dealt with the other questions raised by Mr. Paxton and Mr. Schuster in my replies to other speakers.

## East Midland Sub-Centre, at Loughborough, 10 April, 1923.

**Mr. B. A. M. Boyce:** On page 439 the following statement is made: "The frequency for most electrification schemes in this country, however, is 50 periods per second, which limits the alternator speed to 3 000 r.p.m. Whilst this speed has been found suitable for moderate outputs, it is not sufficiently high to enable the best economy to be realized in small commercial turbines of 1 000 kW and below, a circumstance which has led to the development of geared turbo-alternators for these outputs." I emphatically disagree with this, as with the design of my company employing the double-rotation Ljungström turbine we get the equivalent of 6 000 r.p.m. without the use of gears, and can produce a 1 000 kW set with very high efficiency. With regard to the curves on pages 440 and 441, I should like to know if the kVA rating is with 25 per cent overload or whether it is the maximum continuous rating. On page 442 the author states that long lengths of machine are preferable, but I consider that short rotors with as large a diameter as practicable are the best. The special stator conductor is very interesting and no doubt eliminates eddy currents, but the flexibility introduces difficulties in clamping and the flexible mica insulation mentioned becomes a necessity. I saw recently a large alternator on the Continent with one conductor per slot made up of 120 strips bent in a special way to minimize eddy currents. I prefer the flexible slot insulation to the solid types, though very good results are obtained with the latter. With regard to the type of slot, the enclosed or tunnel type advocated by the author appears to give good results on large sizes of alternators. We use slots of the semi-enclosed type, really a double slot with the winding in the bottom portion; this gives good wave-form, additional reactance and ventilation. I understand that severe heating at the ends of stators has been located to the use of tunnel slots in some alternators. Most of the large alternators which I saw on the Continent had a similar type of ventilation of the stator, but instead of being carried out axially as shown by the author, it was done circumferentially, the air entering at one portion of the circumference and leaving at another. We have had no trouble from instability or reversals of exciters, but ours are comparatively small machines. The stability is obtained by using cast-iron yokes and saturating the cast iron where the main pole joins. With regard to rotor cap spigots I think that their use depends on the relative strength of the metals employed and that the weaker metal should always be on the outside.

**Mr. T. Hall:** What does the author consider to be the best method of drying out alternators? This is generally done in a slipshod manner. I have had a certain amount of trouble during the past 4 or 5 years with the end winding of the rotor, owing to the end bell pressing on the end windings, thus causing the mica to powder. In regard to the question of the pump for supplying cooling water for the air cooler, should a separate pump be fitted or should the cooler be supplied by the main circulating pump, by by-passing the water across the condenser?

**Mr. C. Sutton:** The author is not quite fair in his arguments against the large-diameter machine. We have found that the output of a two-pole high-speed alternator varies at least as the cube of the diameter, so that any increase in diameter decreases the length very considerably. Taking the two machines, dimensions of which are given in the paper, and varying the length as the cube of the diameter, we have the following: 18 000 kVA at 2 400 r.p.m., rotor diameter 33 in., length $108\frac{1}{4}$ in. Dr. Barclay * gave the maximum advisable diameter for 2 400 r.p.m. as 39 in. Now with a diameter of 39 in. the length of the 18 000 kVA machine would be approximately 70 in., a saving of 38 in., or 35 per cent. For the other machine we have: 14 700 kVA at 2 400 r.p.m., rotor diameter 29 in., length 105 in. By only increasing the diameter of the rotor to 33 in., i.e. the diameter actually used on the 18 000 kVA machine, the length could have been reduced to approximately 70 in., a saving of 35 in., or 34 per cent. The great advantage of these shorter machines, apart from the reduction in weight, is that the length is such that no complicated system of ventilation is necessary. The ventilating system described in the paper is not ideal by any means, a particularly weak point being that any cooling air passing between the stator teeth is in direct opposition to the windage from the rotor, and considerable heating of the air must result. In fact it is fairly safe to assume that practically no air flows down the stator teeth but that it is all short-circuited through the axial holes M (see Fig. 16). This will tend to create hot spots in the stator teeth, i.e. just the point where hot spots are dangerous. Another disadvantage of the system is the fact that there are sudden changes in the direction of the air-flow. These should always be avoided. One of the most important factors in any ventilating system is the air velocity. We have many machines working with an air velocity at the cooling surfaces of 8 400 ft. per min., and this velocity has proved very efficient. The only other point I have to raise is with regard to the use of cable for stator winding. While cable may be the best proposition for the prevention of eddy currents, it must be admitted that it is not a mechanical job in any respect. In the first place, when the insulation is being applied to the cable before it is inserted in the slot, great care must be exercised to see that the cable is always supported over its entire length, as if the cable bends, even if the insulation is not damaged, air pockets may be formed, and these should be avoided. Then in threading the cable into the core the cable must again be held absolutely rigid, or otherwise there is grave danger of damaging the insulation. Again, there is always the danger that one of the strands of the cable may have been broken and the end of the broken strand forced into the insulation, thus creating the possibility of a breakdown to earth. One of the weakest points of a stator winding is where the coil leaves the core, and here the cable is at a great disadvantage as compared with a solid conductor. Referring to Fig. 11, it will be seen that there is a considerable length of cable outside the core, particularly in the case of the outer tier, and particular attention must be paid to the support of this cable. We gave up the use of cable many years ago, as we came to the conclusion that it was a much sounder proposition to adopt a solid type of conductor for mechanical reasons and take other precautions for the increase in the eddy-current losses which necessarily follow. With a special design we have found it satisfactory to use a solid conductor for currents as high as 2 000 amperes per conductor at 50 periods. There was an interesting article in the *Journal of the American Institute of Electrical Engineers* for February, 1921, in regard to the eddy-current losses in cables. In this article it was stated that by impregnating the cable with a solution of sodium sulphide ($Na_2S$) the losses were reduced in the ratio of 0·0066 to 0·0013 for 25 periods, and 0·037 to 0·0061 for 60 periods. Has the author ever considered this proposal? I agree with the author that the soundest stator winding is obtained by having separate slot conductors and end connectors, but this surely fixes a maximum limit to the voltage for any size of alternator. In the various discussions on the paper the question of higher voltages has been raised several times, and most designers will agree that it is possible to build machines for higher voltages. On the other hand, if reliability were the first consideration, as it should be, and as the simplest, strongest and most efficient winding can be obtained with one conductor per slot, the voltage that gives this condition should be adopted, regardless of the actual supply voltage required.

---

* See *Journal I.E.E.*, 1918, vol. 56, p. 472.

**Mr. T. P. Wilmshurst:** We have in Derby 20 000 kW of electrical plant made by Messrs. Parsons, and in the course of 12 years we have not had a single electrical breakdown in any way attributable to design or manufacture. I should like to raise the question of air cooling by a separately driven motor fan. The auxiliaries are usually in the basement and receive less supervision than the main plant, and the sudden stoppage of the fan, if not observed at once, might lead to disaster. On our larger machines we have installed a thermal alarm which will operate a buzzer at a certain temperature-rise, and I think that such an alarm should be installed by the makers as an integral part of the machines. I should like to know if the author considers it to be feasible to install on large machines a small fan on the rotor shaft in addition to the main separately-driven fan, of sufficient capacity to carry on at a reduced load; or, alternatively, if he would be prepared, on large machines, to supply two fans each of 50 per cent of the total capacity, as is now done with the circulating pumps. At the same time I am bound to admit that we have never had any trouble due to the stoppage of the fan motor. What, in the author's view, is necessary for the electrical protection of large modern stators? As he has shown, these stators are now so sturdily built that they will withstand sustained external short-circuits. Does he consider that we are justified in abolishing overload protection on our oil switches and relying on the internal reactance and on the use of circulating-current gear, combined with field-suppression switches to look after internal faults? I believe that this practice has been adopted at Gennevilliers and other large stations.

**Mr. J. Rosen** (*in reply*): Most of the questions raised have been replied to in the previous discussions.

Referring to the curves on pages 440 and 441, the kVA output is given on the maximum continuous rating and not on the overload. The other questions raised by Mr. Boyce have been replied to in the earlier discussions.

With regard to the best method of drying out alternators, I would refer Mr. Hall to my reply to Mr. Powell in the Glasgow discussion on page 471. Movement of rotor end windings due to insufficient support will account for the powdering of the mica at the end caps. A separate pump is normally used for supplying cooling water to the air cooler, but many coolers in which the water is by-passed from the main circulating system are in operation. The latter arrangement is more satisfactory if the water in the cooler tubes can be kept below atmospheric pressure.

No such difficulties as were referred to by Mr. Sutton in connection with the ventilation scheme have been met.

I am pleased that Mr. Wilmshurst has had so little difficulty with the electrical plant, and I agree with him in the precautions he has taken to indicate when the fan is shut down. I would refer him to the arrangement shown on page 467 which shows the external fan coupled to a pump motor. I think that this arrangement will meet his difficulties, or, alternatively, his suggestion of using two fans could be readily adopted. I think he would be quite justified in removing the overload protection and depending on the circulating-current protective gear. It is undesirable for a large machine to trip off the busbars because of a momentary overload. On this account overload protection has been abolished in many stations in this country.

## South Midland Centre, at Birmingham, 25 April, 1923.

**Mr. A. M. Taylor:** While information like that contributed in the present paper, as well as that in the recent paper of Mr. Kuyser, is of extreme value both to the users of generating plant as well as to the manufacturers, I think that it would be of still greater value if particulars were collected together from the various users of the plant as to the time each set has been installed, and the percentage of that time during which it has been out of commission due to defects whether in the turbine, the alternator, or condenser. Fig. 2 gives breakdowns in terms of the percentage of alternators installed, but I suggest that this may be misleading, inasmuch as one particular alternator may break down several times in succession, and I presume that this would not appear on the curve. In the United States a most interesting questionnaire was issued by the National Electric Light Association to all the electricity generating stations, and the results appeared in the *Electrical World* (1922, vol. 79, p. 1035), but not, however, in a very intelligible form, owing to the small scale of the photographic reproduction of the chart. I have extracted from that chart the essential information and arranged some of it in the form of Table C, for units in "class 1" service. Similar tables relating to units in "class 2" and "class 3" service respectively give the following average results:

| | "Class 2" service, per cent | "Class 3" service, per cent |
|---|---|---|
| Service demand factor . . | 77·9 | 94·2 |
| Unit operating factor . . | 69·0 | 76·3 |
| Outage, all causes . . . . | 8·9 | 17·9 |
| Turbine outage . . . . | 6 | 10 |
| Alternator outage . . . . | 4 | 3 |
| Condenser outage . . . . | 0·5 | 3 |
| Major non-service repairs . . | 0 | 0 |

The results are expressed in a way which I suggest is exceedingly useful, viz. in terms of the "service demand factor," the "unit operating factor," and the "outage factor." An example of the construction of these novel factors is as follows: 10 000 hours *completed* since erection; 7 000 hours *called on* to operate; hence $\frac{7\ 000}{10\ 000}$ = "service demand factor" = 70 per cent. 6 000 hours actually *in operation*; hence $\frac{6\ 000}{10\ 000}$ = "unit operating factor" = 60

Table C.

| Ref. No. | Speed | Rated load | Service demand factor | Unit operating factor | Outage, all causes | Turbine outage | Alternator outage | Condenser outage | Major non-service repairs |
|---|---|---|---|---|---|---|---|---|---|
| | r.p.m. | kW | % | % | % | % | % | % | % |
| 1 | 1 800 | 20 000 | 34·0 | 30·1 | | 0 | 4 | 0 | 0 |
| 49 | 1 500 | 35 000 | 35·5 | 35·5 | 0 | 0 | 0 | 0 | 31 |
| 46 | 1 500 | 20 000 | 41·8 | 41·8 | | 0 | 0 | 0 | 10 |
| 48 | 1 500 | 20 000 | 45·1 | 45·1 | | 0 | 0 | 0 | 13 |
| 47 | 1 500 | 20 000 | 46·9 | 46·9 | | 0 | 0 | 0 | 12 |
| 25 | 1 500 | 20 000 | 49·3 | 49·3 | | | | | |
| 39 | 1 200 | 20 000 | 53·5 | 51·5 | | | | | |
| 76 | 1 500 | 30 000 | 53·8 | 48·5 | 5·3 | 3 | 1 | 1 | 0 |
| 28 | 1 800 | 25 000 | 54·8 | 53·9 | | | | | |
| 77 | 1 500 | 30 000 | 56·0 | 47·9 | 8·1 | 6 | 1·5 | 1 | 0 |
| 75 | 1 500 | 20 000 | 57·3 | 57·1 | | | | | |
| 35 | 1 500 | 20 000 | 59·0 | 56·0 | | | | | |
| 34 | 1 500 | 20 000 | 59·9 | 54·9 | | | | | |
| 72 | 1 500 | 20 000 | 60·8 | 29·1 | | 32 | 0 | 0 | 0 |
| 64 | 1 500 | 20 000 | 61·8 | 45·7 | | 12 | 2 | 3 | 0 |
| 78 | 1 500 | 30 000 | 61·8 | 55·7 | 6·1 | 3 | 2 | 1·5 | 0 |
| 27 | 1 800 | 25 000 | 62·3 | 61·1 | | | | | |
| 26 | 1 800 | 25 000 | 63·3 | 54·4 | | 7 | 0·5 | 0·5 | 11 |
| 22 | 1 800 | 20 000 | 63·3 | 59·1 | | 5 | 0 | 0 | 0 |
| 40 | 1 200 | 20 000 | 63·3 | 59·6 | | | | | |
| 57 | 1 800 | 30 000 | 63·7 | 54·2 | 9·5 | 0·5 | 0 | 10 (other) | |
| 71 | 1 500 | 20 000 | 63·9 | 54·4 | | 6 | 3 | 0 | 0 |
| 73 | 1 500 | 20 000 | 64·2 | 31·8 | | 24 | 9 | 0 | 0 |
| 41 | 1 200 | 20 000 | 64·8 | 63·5 | | 0 | 0 | 0 | 21 |
| Averages . . | . . | . . | 55·8 | 49·5 | 6·3 | 5 | 1 | 0 | 4·5 |

per cent. 1 000 hours (7 000 − 6 000) out of commission, *through stoppage*, when called upon ; hence $\frac{1\,000}{10\,000}$ = "outage factor" = 10 per cent.

I suggest that if the Institution, or failing this the Incorporated Municipal Electrical Association, could see its way to issue such a questionnaire to all the electricity stations in the country, it would be of immense value, and the results could be discussed before a meeting of the Institution with very great profit to the industry. The period during which plant is actually out of commission is perhaps, from the central station engineer's point of view, more important than anything else. I notice that very large sets are dealt with in the table for "class 3" service. The two 45 000 kW sets average 15 per cent "outage"; the one 40 000 kW set averages 25 per cent "outage"; the four 35 000 kW sets average 20 per cent "outage"; the two 32 000 kW sets average 14·5 per cent "outage"; and the eight 30 000 kW sets average 19 per cent "outage." The average "outage" for the complete table is 17·9 per cent, which is very different from the 5 or the 10 per cent of the author's curve. I am much interested in the author's statement with reference to the importance of getting rid absolutely of tooth ripples in the wave-form, and this too at all loads. I recently examined a case where the following conditions, which are now becoming quite common, obtained, a generating station delivering current at, say, 6 000 volts, feeds through trunk mains at this pressure to a point a couple of miles away, and parallel with this transmission is a step-up 30 000 volt transmission. The neutral point of the generating system is earthed and the neutral point of the high-tension star of the step-up transformer is also earthed. The said star winding of the transformer may give an oscillograph curve which is perfectly free from triple harmonics, but if the generator has an extremely small third harmonic this may pass current in series through the earth connection of the high-tension star of the transformer and then through the capacity of the high-tension (30 000 volt) mains to earth at the distant point, and may return through the capacity of the low-tension (5 000 volt) mains to the generating station busbars and so through the alternator windings back again to earth. In the case which I had worked out I found that there was danger of a capacity current, which might be only of the order of 1 ampere, so affecting the excitation of the step-up transformer as to start a third harmonic in this transformer and, neglecting for the moment the wiping-out effect of the delta on the primary side of the transformer, producing a 10 per cent third harmonic ; the 10 per cent third harmonic acting through the capacity of the line would tend to produce sufficient current to give a 30 per cent third harmonic. Hence a cumulative deformation of the transformer wave would be produced, and, in order to be sure of being free from this, there must be nothing larger than a 3 per cent third harmonic, or a 1 per cent ninth harmonic, in the generator. As above stated, this neglects the damping-out effect of the delta winding ; but the latter is not perfect, depending upon the inductance of the said winding and other factors, and, moreover, different local conditions might so alter the capacity arrangements as to make the case cumulative in spite of the delta winding. Each case requires to be investigated on its merits, but it looks as though even a 3 per cent third harmonic or a 1 per cent ninth harmonic is quite sufficient to be troublesome. I suggest that the above is not a case of resonance proper, but merely depends upon the deformation of the E.M.F. wave of the transformer, a point which was clearly brought out by Mr. J. F. Peters in his paper [*] before the American Institute of Electrical Engineers in 1915, and more recently by Mr. G. Faccioli in his paper [†] last May before the same body.

**Mr. A. T. Bartlett :** The study of faults and breakdowns and inquiry into their causes are always most interesting and useful. The lantern slides which the author exhibited illustrated very interesting faults ; one in particular was a photograph of the bars mentioned in the paper as having suffered from erosion, which proves that no alternator should be run without a filter, or preferably with a closed air-cooling circuit ; unfortunately, to run without a filter is still the practice of some station engineers. The method adopted of measuring the deformation of rotor caps is questionable. It seems impossible that the rotor, sparking point and camera should all remain relatively in the same position ; vibration and windage must cause movement comparable with the quantity being measured. Even with fixed points the spark method of measuring small gaps has proved unreliable. Has the author noticed any cases of permanent deformation in rotor caps ? I have found traces of this, notwithstanding the fact that the caps have been stressed considerably below the limit of proportionality. I should be glad to know if any work has been done to ascertain whether prolonged stress, although below the limit of proportionality, can produce permanent deformation. There seems no doubt that if the stress does not exceed the fatigue load no permanent deformation can occur. I agree that the most satisfactory form of rotor is the solid steel forging. The effect on the exciter current of any sudden change in the stator current is not sufficiently recognized. The stator and rotor form the primary and secondary circuit of a transformer and during a change of current in either there is a corresponding momentary change in the other. Oscillograms taken in the exciter circuit often show intermittent changes in the stator current more satisfactorily than when taken in the main circuit.

**Mr. J. Morton :** In reading through the paper one is forced to the conclusion that the author is an advocate of higher speeds, and from the designer's point of view this is perhaps permissible. Had he, however, been engaged on the supply side, and been obliged to put up with breakdown after breakdown, all on high-speed machinery, he would perhaps alter his views as to reliable maximum speeds. As a matter of fact we in Birmingham have consoled ourselves with the fact that with our 25-period supply we are immune from the additional troubles due to speeds higher than 1 500 r.p.m. With regard to the closed system of alternator ventilation, on page 450 the author quotes a figure of 80 lb. of air enclosed in the system of a 10 000 kW plant, roughly 0·10 cubic ft. per kW. In deciding the volume of air space for the closed system of ventilation on the third 15 000 kW unit for Nechells Station, we fixed the volume per kW at the same value, i.e. 0·10 cubic ft. per kW. In our case, however, the machine is designed for a power factor of 66·6 per cent instead of the usual 80 per cent; consequently, when based on cubic ft. per kVA our allowance is considerably less than that put forward by the author. I shall be glad, therefore, if he will state his reason for adopting this particular value for the volume of air per kW. As regards reversal of polarity on exciters due to overload or short-circuit, the author has got over the difficulty by the addition of a few turns of compounding, but where a battery is installed and properly maintained and is used for excitation, a separately excited auxiliary shunt winding would take up less space and also enable the machine to build up much more quickly.

---

[*] *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, pt. 2, p. 2157

[†] *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 351.

**Mr. T. R. Alexander:** The author's remarks on the magnitude of the eddy currents induced in the modern rotor and the arcing at the spigot of the rotor caps are very interesting to users, and point to the necessity for careful examination at the annual overhaul. The usual insulation under the exciter bearing pedestal to ensure an open circuit for these currents seems open to criticism. In several turbo sets pitting has been observed on the turbine governor gunmetal worm-wheel, which is driven by the steel worm on the turbine shaft. Pitting has also been found on the white metal at the ends of the rotor coupling bearing. Rightly or wrongly rotor eddy currents were thought to be responsible for these defects, but the fact that pitting only seems to occur between different metals may suggest some other cause. After fitting a good earth-connected brush on the alternator rotor shaft near the coupling the trouble was practically but not absolutely eliminated. It would be helpful if the author would give his opinion on such defects; are they the result of eddy currents, and does he think the rotor earthing-brush correct and sufficient to prevent action?

**Mr. H. Joseph:** I should be much obliged if the author could give some further information about the system of moulded insulation for stator windings. I presume that his firm are satisfied that mica flakes held together with varnish do form the best possible slot insulation. Some tests made on empire cloth and an insulating material built up of mica flakes varnished on to thin paper, the materials being of the same thickness, revealed a much higher puncture test with the former than the latter, the mica material showing very variable puncture voltages. I regard linen and cotton tapes not as insulators but as a mechanical medium for holding a film of varnish, and I should be interested to hear if tests have shown that material moulded from varnish and mica flakes has a higher puncture voltage than an equal thickness of empire cloth.

**Dr. M. L. Kahn:** Any criticism which I may make of some of the methods described in the paper is only with a view to obtaining further information on this important subject. It appears to me to be misleading to say that ventilation is the limiting factor of the maximum output for which machines can be built at 3 600 or 3 000 r.p.m. In so far as improved ventilation allows us to rate up any given size of electrical machine, this of course holds good. It does not, however, indicate where the difficulties and limiting features lie. The limiting feature must always be the material at our disposal. The mechanical strength of the steel which can at present be obtained from the steel makers limits us to a maximum possible diameter for each speed. The length of the machine for each diameter is determined by the allowable rotor deflection. These two considerations determine the largest rotor which can be made for a given speed, and this in turn determines the maximum possible output. The author gives in the paper data of some machines with rather long rotors, the deflection on which is necessarily rather large, and this has two objections. In the first place a large deflection means an appreciable relative movement of the caps on the seatings of the rotor body. This is liable to lead to wear of these seatings, so that there is a danger of the caps finally getting loose. Secondly, these long rotors are more liable to vibrate should the rotor be slightly out of balance than short rotors with rather larger diameters. A small displacement of the rotor winding is always possible, due to the expansion and contraction which takes place under normal running conditions. In this case a machine with a small diameter is liable to give trouble with vibration, while a short, stiff rotor would not be sufficiently deflected to interfere with satisfactory running. To use the stranded conductors described in the paper on machines with large outputs has the disadvantage that it involves joints in the winding close to the stator core, as on large machines solid end-connections are desirable, especially with the coil winding described in the paper. These joints are near the hottest part of the coil and, as they are just above the rotor caps close to the core, they cannot be cooled nearly as well as joints at the outer end of the coils, and are therefore more liable to give trouble due to unsweating. The concentric type of coils used in connection with this material, as described in the paper, involves far greater stresses in case of short-circuit than two-layer windings with diamond coils, due to the bunching together of the conductors of each phase of the end winding. This class of winding can be made with joints on one side of the machine only; these joints are right at the end of the coils and can be most effectively cooled. If this winding is used on machines with open slots, the whole of the coils can be fully insulated and tested before insertion, which is a further advantage. By using a large gap, which is in any case required on machines of this type, a large number of slots per pole and fractional-pitch windings and, if necessary, a fractional number of slots per pole and phase, a perfect sine wave can be obtained for the voltage of such machines wound with diamond coils in open slots. I agree with the author that separate fans have a number of advantages for large high-speed units. Apart from the most important point of materially improving the efficiency, there are other features to recommend them. (1) The air supply of the generator can be adjusted in accordance with the load by driving the fan with a variable-speed motor; thus a further saving can be effected in case the machine runs below full load for any length of time, and, moreover, by increasing the amount of air temporarily the overload capacity of the alternator can be increased. (2) The overall length of the plant is materially lengthened. In the case of fans fitted on the rotor, in addition to the length of the fans themselves, space has to be provided to lead to the fans the whole of the air volume required for the machine. This is a very important consideration, as shorter rotors are more reliable, as explained above. (3) High-speed fans are liable to be noisy; in addition, they are difficult to balance, and interfere further with the arrangement for fixing balance weights on the rotor. (4) Separate fans, due to their higher efficiency, heat the cooling air less than fans on the rotor. This difference is quite appreciable, as the losses in the fans on the rotor represent a considerable percentage of the total losses in the machine. (5) The objection that by the addition of separate fans the reliability of the set is reduced, appears to be rather one-sided. It is usually overlooked that not only external fans or motors, but also fans fitted on the rotor may fail. Although such failures are as rare as failures of separately driven fans, the fact remains that these high-speed fans necessarily consist of a large number of highly-stressed parts. The failure of the fan on the rotor is a very much more serious matter than the failure of a separate fan, as it may seriously damage the end-winding of the stator and even lead to the destruction of the machine. External fans running at lower speeds entirely obviate this contingency.

**Mr. J. Rosen** (*in reply*): Mr. Taylor's figures give a very good idea of how a machine's service is interrupted by breakdowns. A questionnaire issued in this country would bring forth some interesting figures, but I think that station engineers are as a rule more interested in surmounting their difficulties than in recording them. All faults are given in Fig. 2, and in some cases they occur on the same machine.

I have already dealt with Mr. Bartlett's questions in reply to other speakers.

Mr. Morton appears to have had difficulties in the past with alternators running at 3 000 r.p.m. I have had experience of difficulties on the supply side, and I feel sure that he will now find that weaknesses in the earlier designs have been found and eliminated. The figure of 1 100 cubic ft. of air in the cooling system of a 10 000 kVA alternator, referred to on page 471, depends upon the design of the air ducts and the foundations. There is no necessity to fix a minimum value; 0·1 cubic ft. per kW is a figure which may be expected in the normal design of foundation.

I have dealt with Mr. Alexander's questions in reply to Mr. Ellis on page 873.

In reply to Mr. Joseph, the insulation formed of mica flakes has proved to be the most suitable for high-speed alternator design. It will withstand the heat and stresses to which the insulation may be subjected. Empire cloth and similar materials have excellent insulating properties, but they are affected in course of time by temperature. I agree that linen and cotton tapes for high voltages may be considered to be a mechanical medium for holding mica or varnish.

I have dealt with Dr. Kahn's question in regard to the deflection of rotors in reply to Major David on page 872. The running of rotors with lower peripheral speeds is quite as satisfactory as that of rotors with higher peripheral speeds, and owing to lower stresses they are more reliable. Prolonged stress has in some instances produced permanent deformation below the limit of proportionality, but this effect is unusual. I have had experience with alternators with the "diamond" winding, but I find that the concentric winding described in the paper has many advantages and no difficulties have been experienced with stresses due to sudden short-circuits.

# DISCUSSION ON "DOMESTIC LOAD BUILDING."*

WESTERN CENTRE, AT SWANSEA, 19 MARCH, 1923.

**Mr. F. Tremain:** I am particularly interested in the heat-storage tanks mentioned; these are on the lines suggested by me for getting a full load on the station and mains during the night. It cannot be too widely known that an electric immersion heater utilizes 100 per cent of the energy supplied, whereas a gas ring with a gap between it and the vessel heated probably utilizes only about 30 per cent, due to the loss of heat to the surrounding air. At Bristol a basic charge of one-eighth of the rateable value per house, plus a charge of 1d. per unit, has been adopted; thus, taking a house rented at, say, £48 per annum, or a rateable value of, say, £40, the basic charge will be £5, and if the occupier spends £20 on electricity at 1d. per unit, he will get 4 800 units for £25 a year, the average cost of the whole being 1½d. In such cases it is well to be prepared with very simple calculations of this character. If one adopts 1d. per unit I suggest that the example be based on 240 units, because 240 pence equal £1. I believe that there is a great opening for ladies to popularize the use of electricity in the home. Electrical engineers can increase the amenities of life by reducing labour in the household, and this can be done in every sphere from the artisan's dwelling to the middle-class houses and the mansions of the rich. The consistencies shown in the consumption charts in the paper are very remarkable. As engineers we have to try to secure a revenue on the machinery and mains for 24 hours in the day, and the domestic load is a very great asset in obtaining that result.

**Mr. J. W. Burr:** I have not yet come across a two-part tariff which in my opinion is satisfactory to both parties. The maximum-demand system seems to be the best multi-part scheme and certainly the most equitable. I consider that any two-part tariff not based on the maximum demand is no improvement on the flat-rate system of charging, and I quite realize that two separate meters and wiring circuits are required in the latter case, but I prefer to simplify the tariff at the risk of duplicating the installation. The figures given in connection with the Billingham Housing Estate would not be applicable to Swansea; and the high diversity factor mentioned certainly would not. In my opinion, heavier capital charges are incurred in giving heating and cooking supply than is generally realized. Recently I found it necessary to incur heavy expenditure on feeders to deal with the heating load, which overlapped the lighting peak for several weeks in the year. I agree that in order to develop the heating and cooking load it is necessary to supply at a low rate; at the same time I think it only fair that this class of consumer should bear its right proportion of capital charges. Not enough emphasis is laid on the indirect saving due to the use of electricity for all purposes. The saving in house decoration, wear and tear of furnishings, and decrease in domestic help required will in most cases save the cost of electricity consumed. I agree with the author that a model kitchen should be provided for inspection, fully equipped and in charge of a qualified lady demonstrator. The question of educating the consumer up to the economical use of the various apparatus, particularly cookers, is a most important matter. At the recent electrical exhibition held at Swansea it was found that while some ladies could cook for six persons a dinner consisting of meat, two vegetables and sweets for a consumption of 2½ units, others took three times that amount to cook the same amount of food, and I suggest that although it would obviously add to the cost of the installation it would pay to fix an easily-read meter on all cookers. In regard to the hiring of cookers, I agree with the author that a rental of 20 per cent per annum on the net cost would be quite satisfactory from the supplier's point of view. I do not, however, think that the consumer would adopt that view, and I suggest that the makers should endeavour to put on to the market a cooker which will compare more favourably in price with the gas cooker, and that the supply authority should endeavour to hire out at a lower percentage of the net cost.

**Mr. J. E. Stewart:** I think that Mr. Burr is right in urging the need of education in the use of cooking apparatus. The want of knowledge in the use of this type of apparatus is very considerable. I made it a point when I advocated the adoption of cookers in Llanelly that there should be a demonstrator for two or three lessons at every house where an electric cooker was installed, and I think I can say that in every one of those houses they still maintain their equipment. In regard to personal experience, in my house, a comparatively small one, I have installed four radiators, two heating plates, a carpet-sweeper, a sewing-machine motor and one or two other little appliances. In regard to bath-heating, I was surprised to find that my consumption increased to 2 300 units per quarter, of which the bath-heating accounted for from 750 to 1 000 units. That is quite different from what I have heard this evening. I am speaking now of the load during the summer months. The water heater for the bath was on for 24 hours per day. I might add, in regard to the life of the electrical apparatus for bath-heating, that it is now in operation after 2¼ years' service, and not a penny has been spent upon it. With reference to the tariffs, I agree with Mr. Burr that it is almost impossible to convince business men of the necessity of a two-part tariff, and it is absolutely hopeless in the case of the average householder; whilst the latter will accept one's word in a great number of cases, as Mr. Burr said, he will always come back to talk about his electricity bill, especially after discussing the amount with his friends. The flat rate is, I think, a good one. I consider it would be very useful to have some charts of houses other than workmen's, because my experience is that they are not the houses that come on peak load. In the better-class houses there are evening suppers, etc., which affect the load in relation to the peak.

---

* Paper by Mr. W. A. Gillott (see page 197).

**Mr. S. B. Haslam** : The relative value of the results obtained when cooking with gas, coal and electricity is a matter of importance not dealt with in the paper. Some little time ago I received some comparative figures of cooking : (1) in a gas oven ; (2) by a coal fire ; (3) by an electric cooker. Similar joints of meat were cooked, being carefully weighed before and after, the final weight including, of course, the fat which had not been lost. The results showed a loss of weight in the electric cooker of only 5 per cent. In a coal-fired oven it was 15 per cent, and in a gas oven I believe it was nearly 25 per cent. That is easily understood, as the products of combustion from a gas fire have to be got rid of, and in leaving they carry off a good deal of the nutriment which should be kept in the meat or retained as fat. One of the great advantages of the electric cooker is that after about the first quarter of an hour the damper can be closed, and these fats can be retained, while at the same time the current can also be switched off to a considerable extent with a considerable reduction in the expense. I think that details of that description should be emphasized, as they have a very material bearing on the subject when comparing costs. The great point to be considered at the present time, whether by manufacturers, station engineers, contractors or users, is the question of propaganda work. At the moment nobody seems to understand exactly whose job that propaganda work is. Station engineers, as far as I can see, appear to be doing everything possible. They have established their showrooms and are quite prepared to give every possible demonstration to other people, but that does not go quite far enough. There is another important section of the community, namely, the contractors who install the apparatus. The contractors of this country are not as alive as they should be to the enormous possibilities of electric heating and cooking, and I think that until they employ the same amount of persuasive eloquence over electric units as is used by gas engineers over the therm we shall not get electric cookers and other electric appliances used in the home as they should be. Manufacturers and station engineers, although they can do more, cannot do all the work.

**Mr. H. O. Davies** : I agree with Mr. Stewart as far as the curves shown are concerned, and I, too, should like to see the results from houses in the residential districts where the chief cooking is done in the evening. I think that the way to popularize electricity is to lower the price of the cookers. I was discussing the price of their electric cookers with a firm recently, and I found that it was about 50 per cent higher than that of a gas cooker. I have asked manufacturers on several occasions for an explanation of this, but up to the present I have not been able to get one. It has been suggested that it is because of mass production, but the castings, apart from the top plates, are practically the same as for electric cookers. I think the hiring of electric cookers at 20 per cent per annum is absolutely impossible when gas cookers are provided at practically one-fifth of that amount.

**Mr. D. Jenkins** : What has impressed me is the lack of attention given to the question as to who is responsible for propaganda. Three parties are concerned : the supply authority, the manufacturer, and the contractor. The supply authority benefits in so far as the more accessories that are sold the more current will be used. The manufacturer is interested in that he gets a direct benefit from the sale of the appliances. The contractor, however, is the man who gets the most direct and immediate reward ; and I wonder if the contractor takes the fullest advantage of the opportunities he has of selling heating and cooking appliances when installing electricity for lighting. The chief difficulty is that, owing to the absence of a two-part tariff, separate circuits are essential for heating and lighting. The effect of this is that although a consumer may want, say, an iron or a vacuum cleaner, he will not actually buy such an appliance because in nine cases out of ten he will not go to the expense of putting in a separate heating circuit. It seems to me, however, that by merely putting, say, one iron in when installing electric light, one is getting in the thin end of the wedge for a greater use of electric heating. I feel that by concentrating on irons to begin with, other heating appliances will follow very easily and quickly. I consider that the onus for real propaganda falls more upon the contractor than upon anybody else. I agree that the contractors have not done so much as they could do.

**Mr. A. C. MacWhirter** : The contractor is not wholly to blame for the present state of affairs. The blame is general. The author refers to the fact that the seller of the apparatus must have confidence in the apparatus which he is selling. My point is that many of the sellers, including the wholesaler, factor and contractor, have no electrical cookers in their own homes. To my mind that is the place where the start should be made. Install the apparatus, get the experience, and then go out to the public and sell. I believe that some manufacturers go to the length of giving special discounts on the first cooker to be used in the contractor's own house, so that he can gain that experience. I am particularly interested at the moment in water-boiling ; I am carrying out a series of experiments which so far are not very encouraging, and I believe that boiling can be done more economically by a coal fire and possibly by gas. I should like to hear what the author has to say on this point. Mr. Burr has referred to the two-part tariff, and I should like to draw attention to an arrangement in Glasgow which I consider to be very suitable and which requires only one meter. There the year is divided into four quarters, with a minimum number of units to be consumed each quarter, charged at lighting rate. In the winter the consumers have to use rather a larger number of units than in the summer time. All the units consumed above that number are sold at a somewhat low rate. The system has proved very advantageous and has encouraged the use of cooking and heating apparatus.

**Mr. R. G. Isaacs :** I should think that at the present time any form of night load would be more acceptable to the supply undertaking than the increase of their day domestic load. That is why I am so impressed by Mr. Tremain's suggestion of heating the domestic water supply at night. It should be quite cheap to install an immersion heater, and a 20-gallon lagged tank could be raised to boiling point with certainly no more than 6 or 7 kWh. At the present time, from observations made in my own house, I know it is costing me 6d. to heat a 20-gallon tank to about 190° F. by the ordinary form of open grate and boiler, and if it were done by gas the cost would be still more. If it could be done by electricity for an expenditure of 6 or 7 units, and the supply undertaking were prepared to supply a purely night load at a low rate (say about 1d. per unit), it would be quite an attractive proposition from the consumers' point of view.

**Councillor B. Cronin :** I am surprised that not one of the speakers has had sufficient confidence to advocate the erection in Swansea of an all-electric house. At the present time the Corporation are contemplating another housing scheme, and if the cost of the houses could be reduced by discarding chimneys and fire-places and installing electric appliances, as the author suggests, then, if Mr. Burr reports that it is practicable, I shall support him. The construction of houses without chimneys was advocated many years ago by Edward Bellamy in his book "Looking Backward," and I have lived to see many of the propositions put forward in that book become actual realities. I think we have arrived at a time in Swansea when we should build houses with all-electric appliances installed, as I believe it would be in the best interests of the public health to do so.

**Mr. W. A. Gillott** (*in reply*) : The discussion has been so much in support of the views expressed in the paper that there is little for me to reply to, and I hope that this general expression of agreement will result in a practical demonstration of the members' convictions by their not only using electricity for their own comfort and convenience at home but also making it possible for the ordinary consumer to use it freely. Mr. Tremain rightly says that ladies can do a lot of good work by advocating the use of electricity in the home, and I would recommend the chief engineers to make a special effort to ensure that their lady consumers and prospective consumers are well catered for. In doing so, however, care must be exercised in placing the subject before them ; it is here that experience is needed, and only thoroughly well-thought-out schemes should be put into operation, otherwise much time and money will be expended for a considerably smaller result than could be secured by experienced handling of the compaign.

Reference has been made to the question of an increase in the cost of supply for heating and cooking and the possibility of the evening cooking coming on the lighting peak. This matter has already been dealt with in my replies to the discussions at other Centres, but I should like to say that it is impossible to give a concrete reply without knowing all the conditions of the particular case. Generally speaking, the evening domestic load does not affect the station load ; further, it is impossible to draw a conclusion as to how a big increase in domestic load will affect any undertaking's supply if its investigations cover but a few instances on its own mains. The effect of 12 fully-equipped houses on different parts of a network is quite different from that of a similar number on one section ; also, 100 such houses would produce an entirely different average result from that of the 12 houses, even if they were grouped in each case. I therefore take this opportunity to emphasize again that before chief engineers incur any large expense upon mains, plant, etc., they seek advice as to how their particular conditions will be affected. Much of the money which is considered necessary in order to give an efficient supply could be, in many instances, diverted to the education of the public upon the uses of electricity, which the majority of speakers have agreed is necessary.

A few speakers have raised the question of who should pay the cost of propaganda work. I am of the opinion this is a co-operative responsibility, and it behoves us all adequately to support the British Electrical Development Association so as to enable them to extend the good work in which they are engaged.

Mr. Davies considers the sum of 20 per cent of the net cost of a cooker to be too much to charge on a yearly rental. In giving this figure I stated that that sum would provide interest, maintenance charges, and capital redemption. It is of course a matter for each undertaking to fix its rental. I believe in charging quite a low rental and adding ¼d. per unit to the price of electricity ; in other words, do not bring the price down to the very lowest at which the supply could be given, but add the ¼d. to enable an efficient service to be rendered to the consumers. This will produce a much better result for all concerned.

I desire to thank all the members who attended the meetings for their kind support and attention, and particularly those who travelled some distance and took part in the discussions. I thoroughly appreciate the value of the speakers' assistance, without which the paper would be of little interest.

# DISCUSSION ON "WORKS PRODUCTION."*

## NORTH-EASTERN CENTRE, AT NEWCASTLE, 26 MARCH, 1923.

**Mr. A. P. Pyne:** The paper deals presumably with the Metropolitan-Vickers system of furthering production. This system is one of the finest in the country, but, although such elaborate organizations are essential to the success of the large concern, I question whether they can be usefully employed by the medium-sized firm. They are certainly too costly for the small works employing a few hundred men. I take it, however, that the author's object is not so much to assert the universal application of the system he deals with, but rather to emphasize the advantages of systematic production. Production may be divided into two main sections, which are interdependent, namely, progressing and costing. As far as the former is concerned some scheme, simple or otherwise, is usually developed more or less automatically to fill the needs of individual works, but cost-keeping is a matter that will not run itself and is far too often neglected. In fact, there are far too many works existing to-day in which correct results are only available quarterly or even annually. In times like the present it is a vital necessity that we should know our costs both promptly and accurately. The author proves this up to the hilt. With regard to establishment charges, accountants tell us that it takes two years to arrive at accurate results. With the widely fluctuating volume of work passing through the shops under present industrial conditions we want to revise our establishment charges every few months (in some cases every month) if we are to be certain of covering them properly. The hourly basic rate on machines is certainly a better way of allocating charges than a percentage on labour. On the other hand it is not so easily applied in the case of small shops, for which I prefer the percentage on labour. The Hollerith card system referred to has its good and bad points. It is of little service in shops where the jobs are small and numerous, as the cost becomes absolutely prohibitive owing to the enormous number of cards to be handled. In dealing with the output for the year the comparative figures given under good and bad management do not sufficiently take into account the human element. I think that anyone with experience of shops working day and night shifts, both before and during the war, will agree that the difference between the cost of day and night shifts in the average works is very much higher than that shown in the table. The figures do, however, show clearly the value of full output and the serious effect that low output has on costs, quite apart from failure to earn the proper proportion of establishment charges. The paper is sufficiently interesting to make one wish it had been somewhat lengthened by, say, the introduction of comparisons with other systems. Again, there are other aids to production on which it would have been instructive to have the author's views, e.g. bonuses to shop foremen. Such bonuses, if the basis is a correct one, are productive of nothing but good, but considerable care must be taken to ensure the achievement of the desired results. For instance, in arranging a bonus a certain fraction should be allocated for output; a certain fraction for the nature of the product; another fraction for the finish or excellence, and so on. This, whilst appearing highly complicated, is not so in practice. I have a bonus system at present in operation depending on no less than six factors, and yet a weekly bonus earned by four different foremen can be calculated by a clerk in five minutes from the usual shop returns.

**Mr. H. W. Miller:** It is now fully realized how important it is to have in every factory a scientific system of planning, progressing and costing; such system must, however, be adapted to the particular class of goods manufactured, and no existing system can be taken as suitable for adoption in any works without modification to meet individual requirements. The great value of the system adopted in the author's works is most strongly brought out in his concluding remarks in regard to the improved output, reduction in manufacturing period, etc., which illustrate most clearly the benefit of introducing a suitable system into an existing works. The tables and information given in the paper rather suggest that the output is of standard designs, and the conditions therefore are entirely different from those that might apply in a factory dealing with diverse production. Some further information would be of interest to indicate how far the works in question is dealing with standard production only. The section of the paper dealing with the scheme for an unemployment sinking fund is of great interest, and some further information as to its application would be of value in view of the difficulty of introducing piecework in certain shops, such as pattern-making and marking-off shops, or tool rooms. The basis of the system is the piecework price, and difficulty appears to arise here from the fact that the piecework price is, after all, determined by barter or mutual agreement. Again, it is those who are working on piecework who have least need of the benefits obtained from the fund proposed, whilst those who most need the benefits, such as crane men, shop labourers and the like, are the men most likely to suffer in times of depression and at the same time are those most deserving of assistance from an unemployment fund. The author refers in many places to the importance of close co-operation between various departments, and his diagrams show how very closely he endeavours to link departments together. Lack of continuity of effort is apt to occur when an organization grows to a point at which work must be handled by consecutive departments under routine methods, and it becomes vital then to sustain the interest throughout all departments. As a rule, in some department of a large organization there is to be found an individual with what may be termed applied knowledge of, or interest in, any particular piece of work, and the ideal organization is one in which all applied knowledge can be effectively made use of throughout the progress of all work as it is handled by the various departments. Such continuity of effort I should prefer to call "team work" rather than "co-operation." One may have perfect co-operation and no interest; what is needed is continuity of interest. If the interest of individuals is sustained beyond their own department, team work is obtained, and I would therefore say that no matter how perfect a system may be introduced for production, interest beyond departmental interest is the great factor in team work, and in the end really the whole basis of production. I do not want the author to feel that I am criticizing the use of a term, as in my opinion there is a vast difference between co-operation and team work. Some further information would be of interest in connection with planning for production. The author states on page 346 that his scheme enables him to foresee, and to make provision accordingly, if the orders received monthly are likely to exceed the shop capacity. It is difficult to see how this can be done if the character of the work is altered, additional buildings required, or considerable extension to plant involved; such changes cannot be made in short periods. The production staff numbering 11, including foremen's clerks, for a works of 700 hands seems extremely small. It would have been of greater interest if the staff figures had included those in the Drawing Office, Purchasing Department, Stores, etc. In connection with costing it is not very clear how the actual time worked is transferred to the costs records. Accuracy in this direction is of great importance, as the chances of error on labour records are far greater than on material records. If a costing system is really efficient it should be quite possible, basing the figures on up-to-date time records, and using current prices for material and labour, to cost a job before it is actually put in hand, and so obtain a valuable check on production costs and estimates.

---

* Paper by Mr. G. H. Nelson (see page 338).

**Mr. J. Gibbins:** The author does not appear to have touched upon the important relation between producing and selling, and the co-operation which is needed between these two at every stage in production. It is quite useless to centre all endeavours on economic production unless at the same time the selling organization is ready and trained to dispose of the goods. I should like to know what method the author adopts to preserve complete harmony between producing and selling. This question may perhaps form the subject of another paper. Regarding sales, it is necessary to formulate a plan, and to pursue it steadfastly; if successful, carry on; if not, then benefit by the experience and try another plan. It would be useful to have the author's views in this connection. As one speaker has already emphasized, team work is the keynote of industry, but it should exist not only between firms or industries, but between works and staff and workers and foremen.

**Mr. C. Turnbull:** It is a common remark with business men that electrical engineers are mere theorists who know nothing about business. They instance the varying charges for current and point out that such variations are not justified, seeing that the same goods, namely electricity, are supplied in every case, however different the rates may be. The author has shown that electricity is not the only commodity that is affected by the Hopkinson method of costing, but that all manufactured goods are vitally affected by the fact that charges consist of stand-by and running costs, and in certain cases the stand-by costs may be of more importance than the running costs. The fact is that such things as diversity factor and load factor are important in the manufacture of all kinds of goods, but the electrical engineer has found it out, whereas other people have not, at any rate to the same extent. If our business men could have the pleasure of hearing a paper such as the present, they would learn that engineers have business ideas as well as business men, and that engineering methods may produce profits where the ordinary methods of the keen business man result in failure.

**Mr. T. Carter:** The paper describes a very elaborate system of works management, and it is doubtful whether such a system could be applied economically unless the works were fairly large. In smaller works one man necessarily does several sorts of work, and if the system described can be applied at all to smaller works it will be only in some suitably modified form. It would be interesting to have information as to the number of men in the works to which the system has been applied by the author, and an important part of the information would be how many of the people employed are on the staff in each department of the system. I feel that the author's system can be applied more efficiently to large works than to small, because when one man has to do several varying kinds of work he probably does them slightly less efficiently than if he were doing one sort of thing only and always; in other words, any slight want of fit between the one-job man and his work will probably be adjusted in course of time more readily than when many-job men have to be employed, with the result that in a large works it may be a little easier to find ready-made, or eventually to produce, round pegs for the round holes of the author's diagram than it would be in a small works to get one man who would fit equally well into several of the round holes in turn or at once. One of the most important points raised by the author is that of unemployment insurance. We ought to distinguish carefully between unemployment insurance and insurance against unemployment, which are two entirely different things. Unemployment insurance means the provision of money for those out of work, and this money must come from those who are working, whilst insurance against unemployment means the provision of work for those who would otherwise be out of work, which is economically a much sounder scheme than the other can ever be. Parliamentary or political action must always be more or less futile in connection with such problems as unemployment, and only the industry itself can really throw sufficient light on the question to enable it eventually to be answered satisfactorily. When that stage has been reached, it may be necessary to go to Parliament for certain powers or to ask for Parliamentary sanction for certain decisions, but the scheme for dealing with unemployment can undoubtedly come in a satisfactory form only from the industry itself. Individual firms can do something to lessen the evils of the situation, but only the industry as a whole can hope to approach the problem with a reasonable chance of success. There are more difficulties in the way than it is possible to discuss here, but it is obvious that whatever consideration is given to the subject will at any rate help to promote understanding of the difficulties, which is the first step towards their removal.

**Mr. R. Robinson :** I should like to ask the author if the Drawing Office is part of the Design Department, as there is no mention of it in the lay-out scheme of arrangement. The author states there is great difficulty in obtaining from the universities men who are sufficiently expert to fill the posts at the head of the different departments outlined in the paper. Am I correct in assuming that these posts are not kept as a preserve for university men, but that any person in the works who has shown the necessary ability will be eligible for any post that may fall vacant ? With respect to the unemployment scheme belonging to the works, I assume that any payment made by the State would not be affected by any payment made from the works, but I should like to be quite certain of this. Regarding the specifications of material sent with orders to manufacturers, has the issue of these specifications been of any appreciable value ? Can the author say what percentage reduction of breakdowns has been effected which can safely be attributed to the inception of these specifications ?

**Mr. G. H. Nelson** (*in reply*) : I have already dealt with the application of the system to small works, referred to by Mr. Pyne, in my reply to the discussions at London and Manchester (see pages 356 and 361). As pointed out, the object of the paper is to emphasize the advantages of a proper personnel and a proper system in all manufacturing organizations, and not to describe in detail a system considered suitable for any works irrespective of size. I do not quite agree with Mr. Pyne that the progressing end of a production scheme " develops more or less automatically," as whether it develops or not depends upon the management, and if the lead is not given from this quarter it does not develop at all. It was particularly the intention of the paper to emphasize the necessity for the management giving the right sort of lead. I agree with Mr. Pyne that there are far too many factories to-day in which the financial position is only available quarterly or even annually, due to the lack of a costing system, and this is absolutely wrong. Further, a great many works have not the remotest idea on the question of establishment charges, percentages, rates, etc., being arrived at by quite primitive methods, and no steps taken to check them. This is quite as bad as, or even worse than, having no costing system at all, as it is likely to mislead, whereas if there is no system at all, one cannot be misled. I note that Mr. Pyne's experience shows that the difference between the cost of working days and nights is higher than shown in the table. However, as mentioned in the paper, the figures in the table represent the actual experience of the works with which I have been associated. I do not claim that the same figures would apply to any works. Referring to Mr. Pyne's remarks in regard to the payment of bonuses to the shop foremen, I would say that I am in full agreement with him ; this has excellent results when properly arranged. I have also found that similar schemes for crane-men, charge-hands, slingers and all labour which affects the output of direct labour, are very beneficial. The actual bases of these schemes must naturally be dependent on the nature of the work and the individual lay-out of factories.

With regard to Mr. Miller's comments that the tables and information given in the paper suggest that the output is of standard designs, I would say that these conclusions are erroneous, the class of machinery being very varied in the works in which the system described in the paper is operating, comprising machines of from about 50 h.p. up to 15 000 h.p. With regard to applying the proposed " unemployment sinking fund " to sections of the workers not on piecework, this is one of the incentives to persuading labour of the classes mentioned by Mr. Miller to accept payment-by-results schemes. Crane-men, slingers, etc., participate in a bonus dependent on the average piecework earning of the shop. I am entirely in agreement with Mr. Miller's comments on " team work," and certainly agree that " team work " is a much better description of what is required than the word " co-operation." One may have co-operation but still lack the real interest which is a necessity to ultimate success, which interest is certainly found in a sports team. With regard to the part of the scheme which enables the management to foresee if the orders received monthly are likely to exceed the shop capacity, this information is given in the charts similar to that referred to in Table 4, which is one monthly chart, a similar chart being made out for every other month. If the total weight due out in any one month exceeds that for which the shop is laid out, then it is necessary to take steps to deal with it, either temporarily, by getting assistance from outside, or permanently, by making arrangements for extensions in the future. With regard to costing, the actual time worked is transferred to the cost records by the men actually booking their time against the various operation numbers and order number. This can be clearly seen from Table 2. I agree with Mr. Miller that accuracy in this direction is of great importance. I have found it most difficult to get the men to do this accurately, so now the shop clerk enters in time-sheets everything except the time actually taken. This latter is entered by the man in the clerk's presence, the clerk visiting the men in the shop daily. Mr. Miller mentions that by a really efficient system it should be possible to cost a job before actually taking it in hand. A scheme such as the one outlined makes this quite possible.

With regard to Mr. Gibbins's remarks, I entirely agree that the proper team spirit should exist between the Production and Selling Departments, but I would point out that the paper is on " Works Production," and that selling is therefore outside its scope. I also agree with Mr. Gibbins that team work should exist, not only within the works but between firms and industries.

Mr. Turnbull's remarks are of considerable interest, and I agree with his comments.

In reply to Mr. Carter, I have already stated the number of hands employed in each particular department of the system in my reply to the discussions in London and Manchester. I very much like Mr. Carter's distinction between unemployment insurance and insurance against unemployment, and, as mentioned previously, I agree that an unemployment scheme by industries is sound.

In reply to Mr. Robinson, I would say that the Drawing Office is part of the Design Department. Mr. Robinson is also quite correct in assuming that the best posts are not necessarily kept for university men. Any man of ability has a chance in the firm with which I am associated. Referring to specifications sent to suppliers, there is no doubt that they have been of considerable benefit. It is difficult to give a definite percentage of the reduction of trouble in consequence of this arrangement, but it amounts to a considerable sum of money annually.

---

## DISCUSSION ON

## "THE IMPROVEMENT OF POWER FACTOR."*

### WESTERN CENTRE, AT SWANSEA, 4 DECEMBER, 1922.

**Mr. J. W. Burr:** The importance of maintaining as near unity as possible the power factor of an alternating-current system is now generally realized by station engineers. Supply authorities sometimes have to install additional electrical plant at the generating station because the power factor of the system is low and not because the steam plant is overloaded. It must also be remembered that low power factor not only affects the plant at the generating station but also entails more liberally designed cables, transformers and switchgear, and it reduces the efficiency of the distributing system and affects the voltage regulation. It is obvious that the increased capital cost and loss due to increased working efficiency should not be distributed over all the consumers irrespective of whether they run with a high or low power factor, but should be borne by those consumers who are responsible for this condition of things. The supply tariff, therefore, should be such as to fix these extra charges on those responsible, so that they (the consumers) can either install phase advancers or other power-factor-correcting plant or pay such an increased charge as will enable the supply authorities to do so. The paper deals with the economic limit of power factor improvement in relation to capital outlay. The way I regard the matter is this. If a number of consumers at the end of a feeder are running their plant at a low power factor it pays to install power-factor-correcting plant if the cost of the phase advancers or other apparatus is less than that of the additional plant necessary to cope with the extra load which the system can handle if power-factor-correcting apparatus were not installed. The installation of this plant would also increase the efficiency of the system and improve the voltage regulation. It must be remembered that this is not only an economic but also a distribution question. My idea is that all consumers should pay on the kVA basis. If this were done they would obviously try to obtain a good power factor. If the power factor on any particular feeder is low the supply authority could, with the difference in price that he receives for kVA instead of kW, possibly erect and equip with phase-advancing plant a substation at the end of that particular feeder, and so release the generating and other plant for useful work, and at the same time improve the efficiency and voltage regulation of that part of the distributing system. Now the question is as to what is the economical limit to power factor improvement. I do not think that it is advisable to try to improve the power factor above 0·95, especially as it means so much to improve it from 0·95 to unity. I think that any station engineer would be satisfied if his power factor did not fall below 0·95 and probably 0·9; it is when it gets in the neighbourhood of 0·7 or less that it becomes very troublesome. To sum up, I think that the consumer who requires a supply of wattless current should be made to pay for it, as it certainly costs something to produce and, after all, the question of power factor is very much in the hands of the consumer. I am referring particularly to the large consumer. Motors should, of course, be run at as high a speed as possible, and the rating of the motors installed should not be in excess of requirements. There is always a tendency to install motors which are too large for the work. It is possible to install phase advancers of various types in the rotor circuits of individual induction motors. Synchronous motors can often be installed larger than actually required by the load, and if these are over-excited they will supply some of the wattless current required by the induction motors. In Swansea there are certain two-part tariffs, one covering the capital charges and the other the running charges. We charge on the kW of maximum demand, but we always insert a clause that the power factor must not fall below 0·8 under any conditions, and in some cases give a varying rebate for a power factor between 0·8 and unity. In future I propose to recommend my committee to charge on the kVA basis, without any restriction in regard to power factor, and I shall advise them to offer such terms as will make it worth while for the consumer to improve his power factor and, failing this, to make it a commercial proposition, as far as the corporation is concerned, to install power-factor-correcting devices in a substation in that particular area.

---

* Paper by the late Dr. G. Kapp (see page 89). The paper was read at Swansea by Mr. R. O. Kapp and at Glasgow by Mr. R. B. Mitchell.

**Major E. I. David:** The author refers on pages 89 and 92 to long-distance transmission where phase-advancing is required during heavy loads, and phase retardation at light loads; this occurs only in very high-voltage lines where the charging current at light loads is sufficient to counteract the effect of the reactance, and for voltage regulation it is necessary to maintain the power factor within a certain range. The author's formula for the economic limit to power factor improvement is a very interesting one, but it hardly applies where apparatus giving a leading power factor costs practically the same as that giving a lagging power factor. This is the case where large salient-pole synchronous motors are used for driving compressors for mines or refrigerating work, the cost of a salient-pole synchronous motor being nearly the same as that of an induction motor for the same output. Thus $c$ becomes zero and $\phi$ becomes 0°. The author's case deals only with the small generating plant with the consuming apparatus adjacent to it, and does not include the case where there are transmission lines and step-up and step-down transformers. Under these circumstances it will pay to improve the power factor in many cases to a slight leading value, as under these conditions the transmission lines operate at maximum efficiency and the regulation and efficiency of the transformers are at their best. A transformer working at unity power factor has a regulation approaching 1 per cent; at 0·8 lagging power factor this regulation may be anything from 4 per cent to 6 per cent. The regulation of a transmission line is also seriously affected by the power factor of the load transmitted. In lines with heavy reactance a voltage boost may be obtained if the load has a leading power factor. The author's costs for plant per kW may be true for present-day values but are considerably under-estimated for the period 1920–22. The author, I am pleased to note, works out practical examples which make the paper of considerably greater value than if the formulæ only were given, but the value of the paper would have been increased if the definite applications of each kind of apparatus were specified. Thus the static condenser is particularly useful where the load exists at the end of a long transmission line consisting of cable or overhead line, this load consisting of a number of small machines, no one of which is of sufficient size for the application of any of the phase-advancing apparatus described later in the paper. A typical example of this kind is given below. Here either a long length of cable had to be duplicated or some means had to be provided for maintaining a better voltage at its terminal.

*Example.—Cable 4 000 yards, 0·03 sq. inch, two in parallel, 3 000 volts supply. Three substations before reaching final substation tapping off to various feeders. Capacity of condenser, 80 μF. Output of condenser 228 kVA, 44 amperes, 3 000 volts, 50 periods, three-phase. Potential transformer across outgoing side of condenser, forming discharge and short-circuiting resistance for the condenser. Installed November 1920. Volts at main station, 3 200.*

| Reading No. | Conditions | Current in cables | Voltage at substation |
|---|---|---|---|
| | | amps. | volts |
| 1 | No load on substation .. | Nil | 3 000 |
| 2 | No load on feeder cables; condenser on. 44 amps. going into condenser leading current .. .. .. | 44 | 3 058 |
| 3 | One pump, condenser off .. | 28 | 2 920 |
| 4 | One pump, 28 amps.; condenser 44 amps. .. .. | 40 | 3 010 |
| 5 | Condenser off. Load 2 pumps | 45 | 2 795 |
| 6 | Load 45 amps. Condenser 44 amps. .. .. .. .. .. .. | 47 | 2 890 |
| 7 | Calculated voltage with 3 cables .. .. .. .. .. | 45 | 2 898 |

| | £ |
|---|---|
| Total cost of installation of static condenser, switch and cable .. .. .. .. .. .. .. | 550 |
| Cost of third 0·03 sq. in. cable, including joint boxes, switches at either end and laying .. | 2 600 |
| Saving by installation of static condenser, approximately .. .. .. .. .. .. .. .. | 2 000 |

The author refers to the Scherbius type of phase advancer for use in conjunction with the normal induction motor, but does not refer to a more interesting machine made by the British Thomson-Houston Company, of which there are two examples in this district. One of these, installed at Britannia Colliery, has a capacity of 25 kVA, 500 amperes, at 600 r.p.m., and operates in conjunction with an 1 100 h.p., 214 r.p.m. 3 200 volt, 50 period, three-phase motor driving a three-crank compressor, having an output of 6 000 cubic feet per minute at a pressure of 75 lb. per square inch. The figures taken in connection with this advancer are given below:

*Example.*—

| | Amps. | Power factor |
|---|---|---|
| Running light. Phase advancer off .. .. .. .. .. .. .. | 100 | 0·4 lagging |
| Running light. Phase advancer on .. .. .. .. .. .. .. | 60 | 0·8 lagging |
| On load. Phase advancer off .. | 183 | 0·75 lagging |
| On load. Phase advancer on .. | 145 | 0·98 leading |

Busbar voltage, 3 200

This type of phase advancer has a definite application in the case of machines with high peak loads and low R.M.S. rating, as Fig. 13 clearly shows that it increases the overload capacity of the machine without increasing the stator currents at normal loads. The author refers at some length to the synchronous induction motor. Some of his remarks with regard to this type of machine are not in accordance with my experience. First, he states that these motors will readily synchronize even under load or overload conditions. My experience is that these motors will not synchronize if the inertia of the external load is high. Secondly, with regard to the air-gap; out of a number of machines running, the average air-gap is smaller than that of induction motors of similar size. The machine illustrated in Fig. 4 gives a more satisfactory result in every way, having a high starting torque with the large air-gap and high efficiency of the salient-pole machine. A machine of this type has been running for some time in Nürnberg, with very satisfactory results. All the above types of machines are suitable for phase-advancing when large-size units are available. When the motor is used in conjunction with a flywheel for a rolling mill, or Ilgner sets for winders, a phase-advancer slip-regulator may be used. An example of this kind of machine is in use at the Melingriffith Works in conjunction with a 550 h.p. motor, giving 10 per cent slip at full load and having a lagging power factor of approximately 0·97. The question of who is to pay for the phase-advancing apparatus, when power is purchased from a power company, should be capable of reasonable adjustment when the consumer recognizes that power factor regulation will give him a more uniform voltage, and further, should enable the supplier to transmit greater loads over existing cables and obtain greater outputs from existing generating plant, and thus ultimately reduce unit costs. Further, phase-advancing apparatus applied to existing motors of moderate or large size increases the overload capacity of the motor itself and of the supply mains to carry these peak loads. A tariff to take account of all these factors and yet be sufficiently attractive to the consumer to encourage him to improve his power factor can surely be arranged. That it pays to improve the power factor is shown by the fact that companies who are both producers and consumers are prepared to spend capital on power factor improvement. A typical example of this is shown in Fig. 10.

**Mr. R. G. Isaacs:** Various methods for improving the power factor are given in the paper, but they are all for the purpose of glossing over the fault that exists in all rotating electric machines, that fault being the comparatively high ratio of magnetizing current to load current. I fear that in the improvement of those methods the fault itself may be forgotten. Power factors are becoming lower for various reasons, among others being the use of low-speed induction motors. Many of those motors were installed at a time when gearing was considered to be neither efficient nor reliable. The installation of a high-speed motor would undoubtedly result in a big improvement in power factor. At the present day, when gearing is considered to be sufficiently reliable and efficient for the largest marine drive, it should be satisfactory for any form of land drive. Again, low power factors are due to the use of induction motors which are too large for the job and are run for a considerable portion of their time on light loads. The power factor in such cases could be improved by reducing the voltage by means of a transformer or, possibly, a star-delta-connected motor. Either method would, of course, need such a tariff as would induce the consumer to adopt it. The price of static condensers is given in the paper as £4 to £5 per kVA. I presume that that figure is for 50 periods. If the frequency were 25 and the price in the neighbourhood of £10 they would hardly be a commercial proposition. It is surprising that phase advancers have made so little headway in this country. In a certain tinplate works where a phase advancer is installed the cost per box of tinplate has been reduced by the price of two units—quite a considerable drop. In this steel and tinplate district it is to this type (with its valuable property of enabling a flywheel to be used to take the peaks of the load) that engineers must look for an improvement in the power factor.

**Mr. J. E. Stewart:** It appears to be the practice to study power factor improvement on a line having at one end a consumer with a set of motors and at the other end a power house, in which case low power factor affects the one consumer only. If there are 20 big consumers on a line, one of whom has a very bad power factor, the other 19 consumers will be penalized by having to put in larger motors. Some apparatus will therefore be required to take into account the fact that the power supply undertaking supplies energy to a new consumer at a power factor of 0·85, say, and that the power factor of the new consumer is, say, 0·85. The resulting power factor, assuming the new apparatus to be of the same size, would be something less than 0·85. If the new consumer corrects his power factor to that of the supply he will have to spend practically as much as the supply undertaking in correcting the power factor from 0·85 to unity. In general, engineering works are made up of 23, 30 and in some cases 40 small motors, and there is hardly room to install apparatus of this sort in any of these works unless it is made very clear to the consumer that it is to his advantage to do so. I am not aware of any tariff that is equitable to the consumer. It is quite easy to improve the power factor from 0·7 to 0·8; but to improve it from 0·9 to 0·95 is expensive, and tariffs at present give only straight-line reductions. The size of motors is vital, and the cause of one of the greatest difficulties with which we have to contend. Works naturally wish to install motors of larger horse-power than is actually required so that there shall be a reserve of power, and they should be allowed to do so. Supply undertakings should do all the necessary adjustment of power factors. Arising out of the question of tariffs from the consumer's point of view, I should be inclined to advocate a flat rate, because practical conditions must be taken into account. I do not doubt the correctness in theory of the maximum-demand system of charging, but consumers understand a flat rate with reductions in price beyond a certain quantity, etc. The principal running costs are the coal costs, and the coal bill varies in accordance with the amount of energy sent out. That is to say, the plant load factor is the most important question from a coal consumption point of view. Power factor correction is possibly more important from the point of view of regulation of E.M.F. on long transmission lines than from any other. Very serious troubles occur on lines under certain conditions; for instance, in some cases a leading power factor produces excess E.M.F. In the early days of the Deptford power station we obtained at the end of the 11 000-volt mains at Charing Cross a greater E.M.F. than that impressed.

**Mr. R. M. Longman** (*communicated*): The statement on page 93, that the rotary condenser is not practicable unless a rebate of 8 per cent is obtainable, should not be taken as ruling out the rotary condenser, as a rebate or diminution of 8 per cent on the bill is neither impossible nor uncommon. Considering a charge on a kVA basis of £4 per kVA per annum as mentioned by Mr. Yerbury, and a load factor of 20 per cent, it will pay a consumer well to improve his power factor from 0·7 to 0·9. The net saving is dependent on his load factor also, and, of course, on the cost of the method of improvement adopted. It appears that if the magnetizing current of a synchronous induction motor be large, the starting torque will be poor, and such a motor should be started up without load. If it has to be started up on a moderate load the starting current will be excessive, and this is very undesirable if the starting be frequent. I should like to know whether the use of a Kapp vibrator effects any alteration in the waveform of the current and voltage waves. I am extremely interested to hear of Dr. Wall's electrochemical advancer, particularly as I recently had some experience with a similar apparatus for rectifying an alternating current. Mining electrical engineers are, I think, very much alive to the necessity of improving the power factors of their loads, and I know of several cases in this area where large Kapp vibrators are being installed. In Fig. 17 the three armatures are shown with their axes all on the same level. This is a decided improvement on the earlier arrangement, in which the armatures were placed one above the other, and the heat from the two lower ones made the top one get very warm. The resulting expansion repeatedly caused it to foul the poles; also the slightest wear in the bearings let the armature down on to the pole-tips.

**Mr. H. Midgley** (*communicated*): To an English engineer some of the points in the paper regarding the calculation of the most efficient power factor may appear somewhat academic, and it is therefore advisable to consider power plants abroad, where electrical energy often is transmitted distances of the order of 100 miles from the point of generation to the point of utilization. A brief examination of such cases will make it quite obvious that a considerable sum of money may be wasted if the most economic power factor is not carefully worked out. As a refinement, instead of the actual capital cost being brought to a minimum, the calculations for the most economical power factor may be based on a minimum annual cost. In this case, the economical lives of various apparatus must be taken into account. For instance, in municipal work the maximum period for the paying off of running machinery is 20 years, whereas cables need not be paid off until 30 years after installation. Assuming interest on capital at 5 per cent per annum, and sinking fund accumulations at 3 per cent (net), the total annual charges for a 20-year life are 8·72 per cent, compared with 7·1 per cent for a 30-year life. Basing calculations on the annual costs instead of on the total cost will make very little difference in the final result, but it is perhaps as well that this alternative method should be kept in mind.

**Mr. R. O. Kapp** (*in reply*): It has been suggested that it would be fairer to make the price adjustment for power factor vary, as it costs more to correct from 0·9 to unity than from 0·8 to 0·9. This is quite true, but it seems to me that too complicated a tariff would operate against power factor improvement, and as engineers we should aim rather at a rough-and-ready adjustment sufficiently near the facts to achieve its purpose and which could be understood by the consumer, than at a tariff which might be more scientifically fair but might involve too complicated a refinement. In the long run that tariff will prove best which results in the greatest power factor improvement, because it would result in the greatest economy to the power company and enable electricity to be sold most cheaply. The tariff which achieves this is, I think, more to everyone's advantage than one which is based on a careful estimate of exactly what it costs each individual consumer to improve his power factor. A point raised by Major David and Mr. Stewart, which will become more important with greater centralization of the generation of electricity, is the bad regulation due to low power factor. This occurs wherever an area is supplied through transformers, and it means that a consumer with a bad power factor is causing unsteady voltage in his area, so that he becomes a nuisance to his neighbours. I think that if this were more fully realized, power factor improvement would become more popular with consumers.

## SCOTTISH CENTRE, AT GLASGOW, 10 APRIL, 1923.

**Mr. C. W. Marshall:** It seems obvious that the consumer of electricity should provide for his own supply of wattless current, except in cases where the supply is very small, as this eliminates the necessity for increasing the size of alternators, transformers and cables beyond the minimum necessary for transmission at unity power factor. The figure given in the paper as the cost of static condensers is £3 per kVA. On the Glasgow system the alternators cost £1·25 per kVA, step-up transformers £0·6 per kVA, step-down transformers £0·9 per kVA, and main transmission cable £0·4 per 1 000 yards per kVA. These items alone exceed the figure given above. In any definite case the figures can be examined in this way and the most advantageous method of supplying the consumer can be settled. Regarding the section on tariffs, the most serious drawback to the methods of charging suggested is that no really satisfactory kVA meter has yet been devised, so that no matter how desirable such tariffs may be it is impossible to carry them out in practice. A further difficulty is that it would be almost impossible to persuade customers to adopt the tariffs, owing to the difficulty of explaining them.

**Mr. R. Nelson:** The most interesting part of the paper to the practical man is the description, at the end, of the various methods which have been employed of meeting this power factor difficulty, and I can confirm the statement that in the Yorkshire district a number of collieries have installed condensers with considerable advantage. Broadly speaking, the cost of the condenser is recovered in from two to three years from the time of its installation. Many collieries have a very poor power factor, and improvement to 0·8 is usually aimed at. This is approximately the figure which the supply authority expects its power users to attain. One important power company in the north of England do nothing beyond inserting a clause in their power supply agreements to the effect that the power factor of each item of plant shall not be less than 0·8 at full load. The Madras Electricity Supply Corporation base their tariff on an assumed power factor of 0·8. They offer a rebate if the power factor exceeds 0·8, and a corresponding penalty is imposed if it falls below that figure. A similar arrangement is in force in Calcutta. The Commonwealth Edison Company of Chicago reserve the right to enter consumers' premises to test the power factor once in every six months during the life of the contract. If the power factor is below 0·7 the Company reserve the further right of withdrawing the supply or, alternatively, of taking the maximum demand as:

$$\frac{\text{Maximum demand in kilowatts} \times 70}{\text{Average percentage power factor}}$$

The power factor is measured at the point where the current is metered, and the maximum demand is determined and fixed as above mentioned for six months, i.e. until another test is made. The Commonwealth Edison Company appear to be satisfied with a somewhat lower overall power factor than is the aim of most supply authorities in this country, but the general character of their load may of course be a ruling factor; they have, I believe, a very large d.c. traction load.

**Mr. G. G. Braid:** So far as the Glasgow tramway system is concerned, we have no trouble with the power factor. Of course the load consists almost entirely of rotary converters, and, owing to the fairly large capacity of the feeder cables, the power factor averages about 0·98 leading. There are certain troubles and difficulties which are always to be found in a.c. working; these include low power factor, hysteresis losses, eddy-current losses, and inductive interference troubles. All that can be expected is to reduce these troubles to a greater or less extent. Methods of improving the power factor have been very fully dealt with in the paper, and little more need be said about them, but I think it would be a good thing if the British Engineering Standards Association would draw up a specification for induction motors, or indeed a.c. power plant generally, which would call for a reasonably high power factor at all loads. So far as tariffs are concerned, the general opinion seems to be that the charges should consist, first of a fixed kVA charge, which is fixed by multiplying the maximum demand in kilowatts by the average power factor, and secondly, of a running charge based on the actual kilowatt-hours used by the consumer. Neither of these charges is strictly right. At the time of maximum demand the power factor is usually highest, and hence the kVA charge is too high; on the other hand, the running charge is too low, as the $I^2R$ losses during all the time the plant is running depend on the power factor, and a small increase in the running charge should be made to cover these losses. I do not, however, advocate that these allowances should be made; tariffs are already far too complicated; they necessitate a multiplicity of meters and allowances, including a maximum-demand allowance, a coal clause, a wages clause, and now a power-factor clause. I do not envy the power supply engineer who tries to explain the reason for all these clauses to the ordinary non-technical consumer. He may explain them to his own (i.e. the power engineer's) satisfaction, but the consumer often feels at the back of his mind that he is not being fairly dealt with; he cannot understand, and becomes suspicious. It would be much better if a fairly flat rate could be introduced, say, one for lighting and another for power and heating, with reductions for large consumers and power taken during the periods of light load, and perhaps some restrictions or penalties for cases of very low power factor. Even if a slightly higher charge were then made to the consumer so as to cover risks, he would, I think, be more satisfied, as he would then know exactly for what he was paying.

**Mr. F. H. Whysall:** My own feeling with regard to the question of power factor is that it has been neglected by the power companies. Most large corporations or municipal supply undertakings with a large non-inductive load and a large proportion of d.c. supply are not very much concerned with the question. In Greenock we have a good power factor and have not been much troubled with the matter. In one or two isolated cases we have had to take serious notice of the question, and my experience has been that it is comparatively easy to explain the position to a consumer, and there is little difficulty in getting him to conform to our ideas on the subject. We are always glad to supply consumers with a specification for suitable power plant, and by getting them to replace inefficient or unsuitable machines by others to our specification we have gradually effected improvement. We put in a static condenser as a remedy for a very bad case, and where the supply is taken at some distance from the power station I think a static condenser is very satisfactory. Our experience has been that since its installation we have had no trouble of any kind whatever. The power factor question will, in my opinion, gradually cease to trouble us as people become educated to the requirements of electric supply authorities. After all, in a certain sense it is a disease which has afflicted us, and we are applying remedies now, but in future we shall employ preventives. With regard to the question of giving rebates to a consumer with a good power factor, it has been our practice to give a 15 per cent rebate if the power factor was 0·8, and this rebate is withheld if the power factor falls below 0·8, but so far we have only insisted on this under normal load conditions. In cases where the power factor has fallen below this figure at times of light load we have taken no notice of it. The difficulty in recording kVA has been mentioned, but I think that we shall overcome that very soon. We have been experimenting with the two-meter method, and we find that we can get a commercial figure of the average power factor for any given period. Where necessary we can, of course, very readily obtain the actual kilovolt-amperes, and if necessary we can threaten to charge the defaulting consumer on a kVA basis.

**Mr. A. E. Kelly**: I have had some experience of several methods of power factor improvement mentioned in the paper, and they all have their peculiar characteristics. The Kapp vibrator is a particularly simple piece of apparatus and has the advantage that it can be adapted to almost any slip-ring motor. In a case I have in mind, the motor was delivered before the phase advancer and was run without it, but it would not take its full load, and the stator current was so large that excessive heating was caused. As soon as the Kapp vibrator was fitted, the machine ran well; and the power factor was improved from 0·65 to 0·95, the current being reduced from 65 amperes at 6 500 volts to 45 amperes. This reduction is equal to 69 per cent if the current is taken at 0·65 power factor, and shows the saving effected by the use of a phase advancer. The other pieces of apparatus mentioned by the author also show good results, and if all consumers realized the effect of such auxiliary appliances they would install them more readily. The supply undertakings are entitled to give some rebate for the saving in mains, or the increase in carrying capacity of their present mains, and this is generally done. One of the difficulties is to get a measure of the average power factor in any consumer's supply, and the author has shown how this can be done. I should like to know of a cheap method of metering which can be adapted to a supply already measured in kilowatts, the meter being easily read and the method readily understood by the consumer.

**Mr. A. E. McColl**: I do not think that many of us realize actually what low power factor costs us. It is only when the question comes to be considered carefully that an idea of the very large sum involved annually, either in the form of increased capital cost or increased operating costs, is arrived at. If we look at the capital cost side we find that, for a power factor of 0·7, cable transformers and alternators require to be 43 per cent larger than would be the case for a system operating with unity power factor. If we review the additional costs incurred on the operating side, we find that our network losses are, under the conditions given, 43 per cent greater than would be the case with unity power factor, and this notwithstanding our increased capital expenditure on the network. In the power station we probably lose 0·6 per cent in efficiency on each alternator, due to the difference in efficiency between unity and 0·7 power factor. Then there is a further loss due to each alternator being 43 per cent larger than is necessary to meet the same kW demand at unity power factor. In the transforming plant we have a similar loss, due to the lower efficiency at 0·7 power factor. Then again, we lose on the individual transformers owing to each transformer being larger than is necessary to carry the kW load of the consumer at unity power factor. In the power station we increase the operating expenses by running additional plant to meet what is purely a kVA and not a kW demand. The impaired voltage regulation introduced by low power factor lowers the value of the service given at the consumer's terminals, and an indefinite loss of revenue results because of this impaired voltage. On the average power system we should probably find that the difference between the units sent out and the units sold is about 4½ per cent less for unity power factor than for 0·7 power factor. There is a further influence which power factor has on the cable system and switchgear. For the same kW demand the distribution system at 0·7 power factor has only 70 per cent of the resistance necessary for a unity power factor demand, and, as previously pointed out, the alternators are 43 per cent larger. The consequence is that the short-circuit current is very largely increased, and switchgear and the expenditure thereon are increased in proportion. In order to limit the destructive effects of the increased short-circuit current we install reactances, which have the effect of still further lowering the power factor. I do not agree with Mr. Whysall that power factor troubles will cure themselves. I think it is necessary to aid in the cure by the imposition of suitable tariffs. The Clyde Valley Company have had a tariff in operation for two years now, and consumers are asking to be put on to it. Speaking generally, we have not experienced any great difficulty so far in conveying an understanding of power factor, particularly where the consumer thinks he is obtaining something for nothing, as happens where synchronous plant is already installed. Of course it is always necessary to demonstrate to consumers that the benefits are such that the rebate allowed will suffice to pay the interest charges on the phase-advancing plant. In all the cases I have investigated where it was found necessary to raise the power factor of non-synchronous plant, there is apparently no competitor of the static condenser. Adoption of the rotary condenser is precluded by the increased losses, including operating expenses, etc., the additional bill for kilowatt energy leaving insufficient margin to cover the interest and other charges.

**Mr. J. F. Nielson**: I wish that Prof. Miles Walker could give some simple method of explaining to the non-technical consumer, or non-electrical engineer, what is meant by power factor. I am sure that many supply engineers must have experienced the difficulty of explaining to consumers what is meant by power factor, and will sympathize with those who have made the attempt at a meeting of directors. For the general improvement of power factor in a works' installation, the static condenser appears to me to offer the greatest attraction, more especially if the supply undertaking's system of metering is such as to give the consumer the advantage of "off-time" phase-advancing. For instance, a consumer may find that as he approaches the end of a quarter, his wattless component meter is lagging further than he expected, and he may think that it would be to his advantage to leave his static condenser continuously in circuit until the wattless component has been wholly or partially cancelled off. My own experience in this connection may be of interest. Fifteen months ago we installed a 600-kVA 4-unit condenser together with an auto-transformer raising the pressure from 440 to 600 volts. When it was put into service we were approaching the end of the first quarter of the year, and our wattless meter showed that we had a considerable leeway to make up if the power factor, which hitherto had been about 0·75, was to average unity at the end of the quarter. With the help of this condenser the leeway was made up, and since then we have maintained constantly a power factor of unity and have thereby obtained the full amount of rebate allowed by the supply company. By the saving thus effected we have repaid fully 25 per cent of the original cost of the installation of this condenser, and it should be borne in mind that we bought it at a time when prices were high, the cost being nearly £8 per kVA installed. I should remark that our supply is at 25 periods; at 50 periods the necessary capacity would be halved and the cost correspondingly reduced. I think Mr. Nelson stated that from his experience a condenser should pay for itself in about three years' time, and at the present-day cost I think he is about right. If in the future our load should increase beyond what these condensers could handle, I think we should be disposed to tackle the problem by improving the power factor of some of our large induction motors by means of oscillating phase-advancers. The objection to installing such plant for general improvement of power factor is that in dull times large motors, such as we have, are not always in service. The initial outlay on these oscillating phase-advancers is very much less than for a static condenser of equal kVA capacity; it is in the neighbourhood, I believe, of £1 per kVA. I have some figures which show, for instance, that a 600 h.p. induction motor can be fitted with an oscillating phase-advancer sufficient to recover about 300 kVA and improve the power factor of the motor from 0·91 lagging to 0·98 leading.

**Mr. A. S. Hampton:** I am quite in accord with Mr. Nielson in his remarks about the difficulty one has in expounding the power-factor clause. Another point which has occurred to me in this discussion is that Mr. Whysall gives a rebate of 15 per cent to those consumers who have a power factor of 0·8. I know no other supply authority which can do that. In the paper mention is made of the Scottish Central Power Company having a difficulty in making the claim for poor power factor, but in a recent agreement that Company insisted on a power factor of 0·8, and the agreement contains a penalty clause for any power factor below 0·8, but they have certain rebates for good power factor. The Greenock arrangement of giving 15 per cent rebate is rather good.

**Professor Miles Walker** (*in reply*): The figures given by Mr. Marshall for the costs per kVA of different kinds of plant are interesting. He does not give the cost of phase advancers attached to induction motors. The cost of these is very much less than £3 per wattless kVA measured on the line.

It would be well if more electrical undertakings would imitate the efforts of the companies cited by Mr. Nelson in the direction of power factor improvement.

I am glad to hear that Mr. Whysall does not find such a very great difficulty in explaining a tariff to his customers. One way of explaining the effect of low power factor to the lay mind would be the following: "Some kinds of plant take more electric current for a given output than others. This is because there is too much back-lash with the volts. If the volts and amperes are geared closely the current taken is less. The supply companies are prepared to make concessions to consumers who use less current for a given power taken. We will fix an ampere-hour meter with a maximum-demand indicator attached. The price you pay for your power will depend upon the readings of these instruments. All you have to do is to keep down the readings of your ammeter. This can be done by installing such and such kinds of plant."

It is difficult to believe that an ordinary lay business man cannot understand the reduction of 65 amperes to 45 amperes as in the case quoted by Mr. Kelly.

Mr. McColl has not stated the case too strongly in pointing out the saving in plant effected by improving the power factor. In fact, the case of the turbo-generator is even stronger than stated by him. A generator to run at 0·7 power factor would cost as much as a generator to deliver 60 per cent more output at unity power factor, and it would not be as efficient. The limit in output in a turbo-generator lies in the field magnet, and a given field magnet can deliver much more kVA if the power factor is unity. A small addition to the armature copper would enable the generator to be run at about twice the output at unity power factor.

The benefits mentioned by Mr. Kelly, accruing from power factor improvements by means of a Kapp phase advancer, have been experienced elsewhere in many cases, and the Leblanc type of phase advancer can show even better figures because with it the power factor of the motor current is completely under control. Moreover, there is only one commutator instead of two commutators to look after. Another advantage of the Leblanc type is that it can be driven at a high speed, so that the machine is much smaller than the Kapp vibrator and the efficiency is higher. It requires no direct-current excitation.

# THE APPLICATION OF A REVOLVING MAGNETIC DRUM TO ELECTRIC RELAYS, SIPHON RECORDERS AND RADIO TRANSMITTING KEYS.*

By N. W. McLachlan, D.Sc. (Eng.), Member.

(*Paper first received 28th February, and in final form 3rd May,* 1923; *read before the* Wireless Section 11*th April,* 1923.)

Summary.

This instrument consists essentially of an iron drum with an annular recess, in which are situated one or more coils of wire, the ends being connected to pairs of corresponding slip-rings. The drum is mounted on ball bearings, and its periphery, which is shod with cast-iron rings, is machined to run true to 0·0001 in. A small iron or steel shoe fits accurately the curvature of the rings. When a current passes through the coil the drum is magnetized, and this causes the shoe to be pressed on the rings with considerable force. Thus, if the drum is revolved, a pull is required to cause the shoe to slide relatively to the rings. The magnitude of the tangential pull thus obtained is many times greater than that calculated from the product of pressure due to magnetic attraction, using the formula $B^2A/8\pi$, and an assumed coefficient of friction $\mu = \frac{1}{3}$. Subsequent experiments show, however, that the value of $\mu$ is about 0·6. The ratio of experimental pull to calculated pull (taking $\mu$ as 0·6) depends on the flux density at the shoe contact, and may exceed 50. Thus the operation of the device appears to depend on some form of cohesive action incited by magnetism. The present paper deals with this phenomenon, but more particularly with its application to electric relays, siphon recorders for line and radio-telegraphy, and transmitting keys for radio-telegraphy. The electric circuits for single-current, double-current and valve-circuit working are described in detail.

Table of Contents.

Section
(1) General outline.
(2) Details of construction.
(3) Single-current working.
(4) Double-current working.
(5) Speed attainments.
(6) Miscellaneous effects.
(7) Valve-circuit working.
(8) Tape records.
(9) Features of the apparatus.
(10) Transmitting key.
(11) Transients at make and break.
(12) Oscillograph records.
(13) Power controlled by key.
(14) Sliding force between drum and shoe.
(15) Dynamic theory.

## (1) General Outline.

The essential components of this device are (1) a revolving soft-iron drum having a recess in which are situated one or more coils of wire coaxial with the drum, the extremities of the coils being brought out to corresponding pairs of slip-rings; and (2) a soft-iron or steel shoe which rides on the periphery of the drum. When current circulates in the coil, the magnetic attraction between the drum and shoe causes the latter to cling to the drum, and a considerable force is required to cause relative sliding movement between the two surfaces. This force can be utilized to actuate relay contacts, a siphon or other suitable inking apparatus. The same principle has also been applied to the operation of signalling keys, but there are other applications beyond the realm of radio-telegraphy which are not treated in this paper, e.g. brakes on motor vehicles.

The working of the instrument will be readily understood on reference to Fig. 1, which shows in plan and elevation the general arrangement of a recorder. The revolving drum of well-annealed Swedish iron is mounted complete with two coils and corresponding pairs of slip-rings in ball bearings. One end of the shaft is connected to a 15/1 worm reducing gear, the worm being driven by a variable-speed electric motor of 1/20 to 1/8 h.p., running at a maximum speed of about 3 000 r.p.m. In order to minimize wear, two cast-iron rings are forced over the drum, and these form the rubbing surfaces for the shoe. The latter is made from a ring of Swedish iron, Lowmoor iron or steel, and is fixed to a brass hook by means of a screw. The shoe rides on the revolving cast-iron rings, and side play is prevented by a projection on the hook which fits into the annular recess in the drum. One end of the hook is coupled to a weak spring $X_2$ which serves to hold it in position, and the other end goes to a rocking lever pivoted on the aluminium crank L. On the other side of the rocking lever is a strong spring $X_1$ which in the absence of signals holds L against the stop S. The tension of $X_1$ can be adjusted by a milled nut. A pad can be provided to ensure cleanliness of the ring surfaces, but it is not absolutely essential, and in general the apparatus functions better without it.

The silver siphon A passes from the inkwell B through the lever L, where it is securely held by a locking device and projects about $\frac{1}{16}$ in. beneath its lower face, resting on the paper strip which is pulled from the drawer in the base of the instrument by the paper drive D. When the revolving drum is magnetized by the signal current, the shoe presses on the cast-iron rings and is carried round, thus pulling lever L on to stop M, where it is held until the current is interrupted. On cessation of the current, spring $X_1$ draws the lever back to the stop S. Thus the transverse motion of the siphon over the moving paper strip produces the record. Owing to the large force and the relatively small inertia of the moving parts, the appearance of the tape, especially above 100 words per minute, is vastly different from that obtained with the usual pattern of siphon recorder.

---

* British Patent 176 932 of 1922.

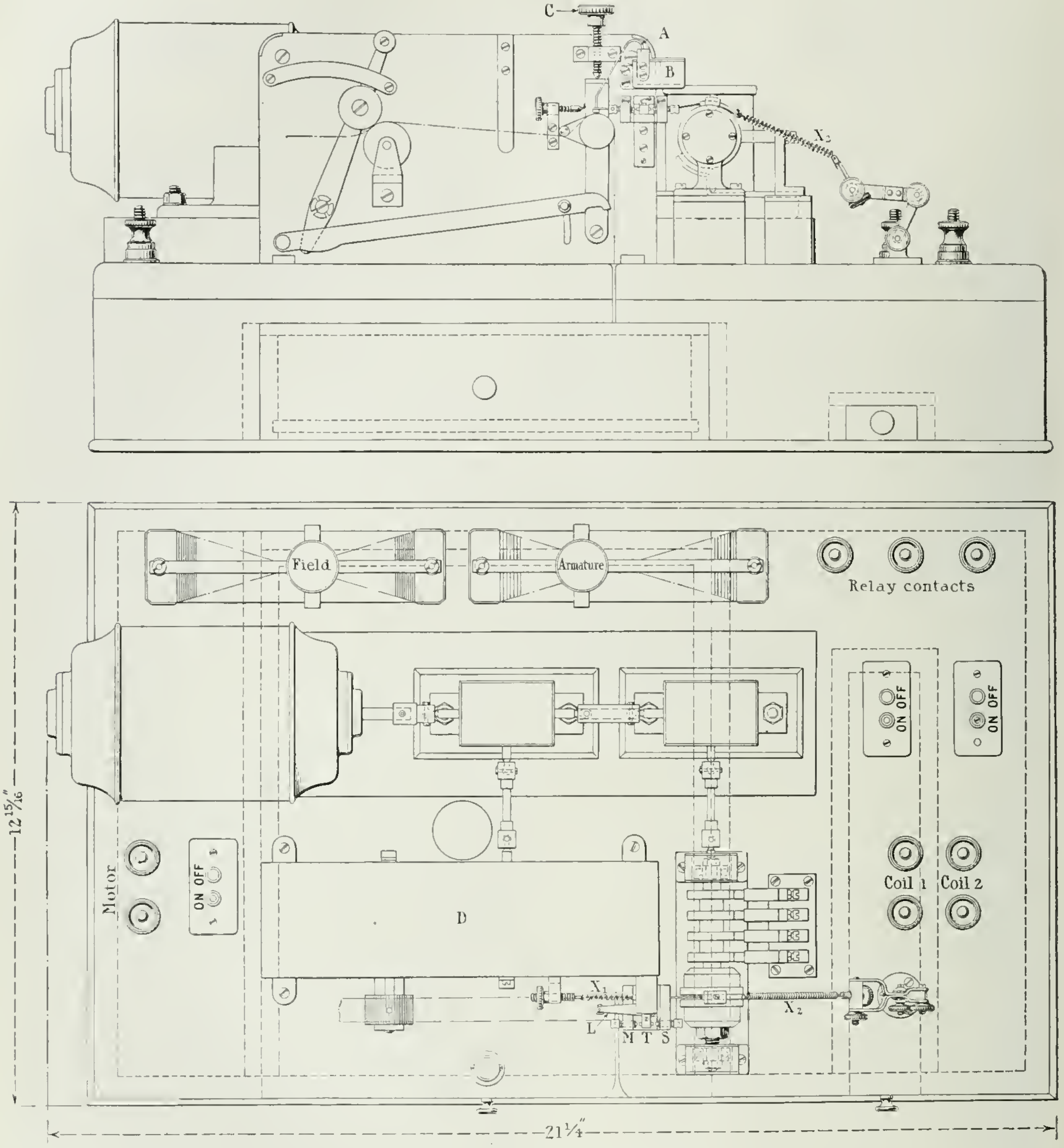


Fig. 1.*—Plan and elevation of general arrangement of recorder complete with variable paper drive. Scale about 3/10 full size

[Note.—Spring $X_2$ is not extended during operation as shown in this figure.]

* In this figure the shoe should be the same width as the cast-iron rings, and the pad should not be shown.

The recorder is made in two forms which are identical except for the paper drive and the front plate. In the first form there is a variable friction gear for altering the speed of the paper, although this can also be done by means of the motor rheostats. The speed of the drum can, therefore be controlled independently of that of the paper. In the second form there is no friction gear and the speeds of the drum and paper are altered simultaneously. This construction is more economical although less flexible than the former. In each type the motor and gears are insulated from

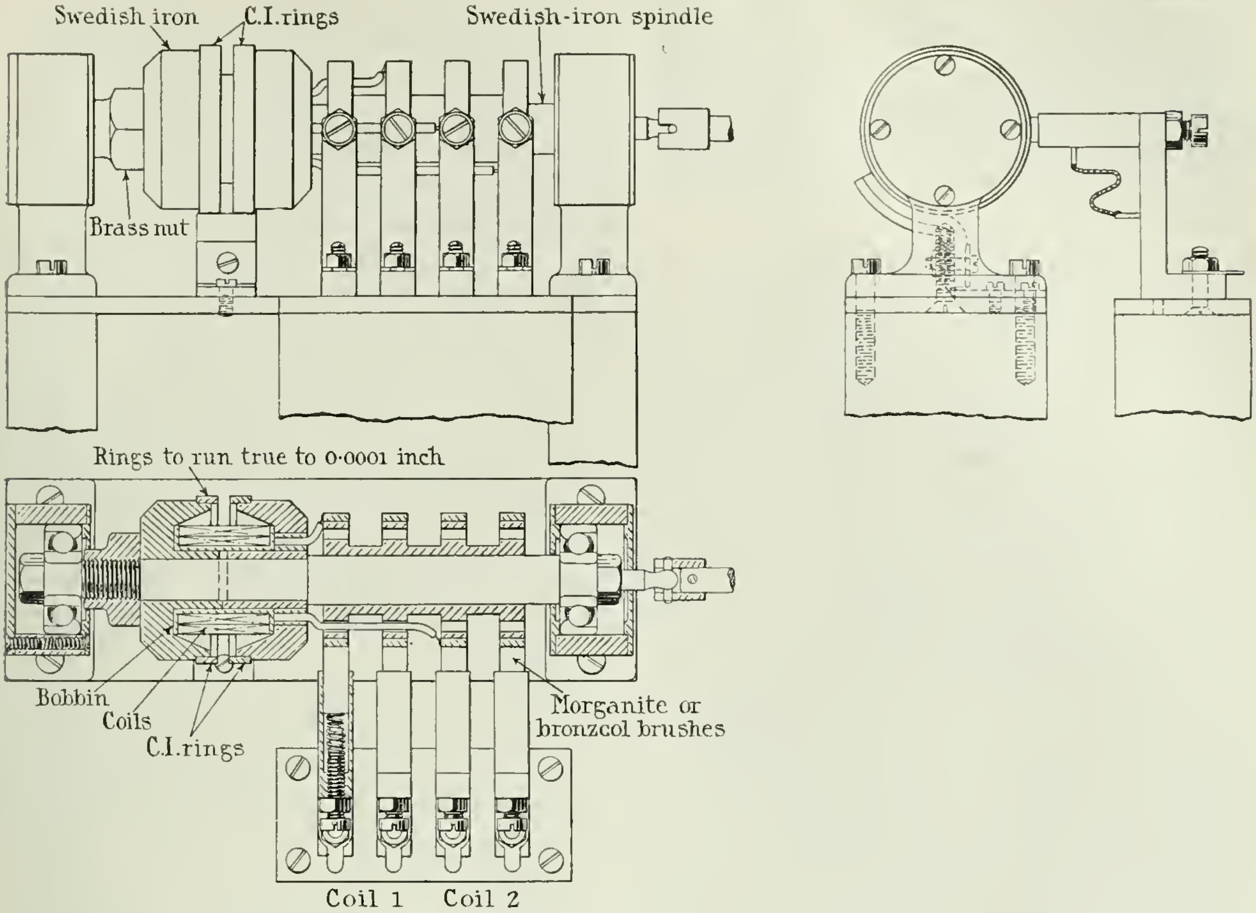


Fig. 2.*—Arrangement of drum and slip-rings of relay or recorder. Scale about 7/11 full size.

* The pad should not be shown in this figure.

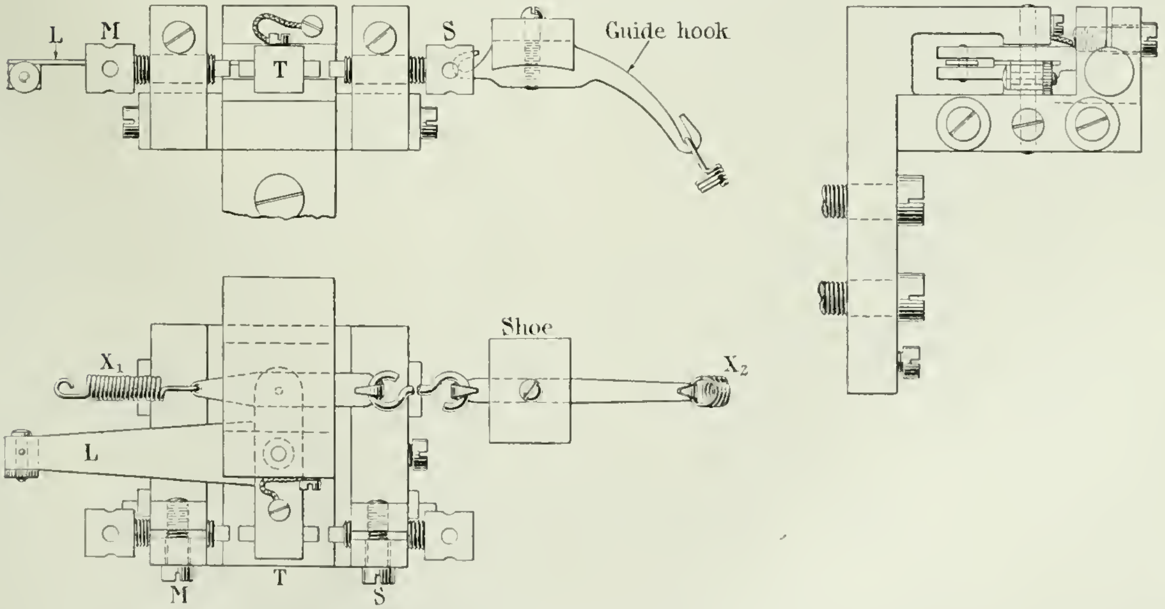


Fig. 3.—Arrangement of recording mechanism. Scale about 5/4 full size.

the wooden base by felt pads which serve to lessen the noise which would accrue from the hollow base acting as a sound box.

In its relay form the instrument is identical with the recorder except that there is no paper drive, the motor is smaller and the contact arm is longer. The diameter of the contacts depends on the purpose for which the relay is used.

### (2) Details of Construction.

The constructional details of the drum and coils are shown in Fig. 2. The complete drum assemblage is so designed that it can be lifted bodily from the wooden base, mounted in a lathe and turned on its own centres. This has been specially arranged in order that the cast-iron rings can be made to run true to 0·0001 inch. In carrying out experimental work on the first model various coils were tried, and it was essential to dismantle the drum when exchanging coils. If the parts fitted accurately there was no need to re-true the drum, provided the two collars were reassembled in their original positions. Allowance is made for this contingency in the design of the spindle and collars. The magnetic properties of the drum and spindle call for careful consideration to obtain optimum results. As the drum revolves, the variation in reluctance of the path through the shoe should be the least possible, i.e. the drum should have uniform magnetic properties radially. With this end in view the Swedish iron ought to be carefully selected and thoroughly annealed, since the heat treatment and subsequent cooling are of vital importance in magnetic material where homogeneity is a desideratum. Discrepancies in the radial properties of the drum can be detected during motion by connecting one coil to a battery and the other to an oscillograph or a galvanometer. A kick of the galvanometer indicates a variation in reluctance.* With a sensitive galvanometer, a kick can be observed when the battery current is zero. Radial homogeneity is not readily attained with commercial metal, but by making the shoe as perfect a fit as possible on the drum, getting the latter as nearly circular as present workshop practice permits and using the electrical circuits described hereafter, excellent results can be obtained continuously.

The method of attaching the shoe to the brass hook is shown in Fig. 3. The line of pull on the hook at the heel and toe of the shoe should be so adjusted that rocking does not occur, and the tension of spring $X_2$ and its inclination to the horizontal should be the least possible. This adjustment ensures that during spacing the natural friction between drum and shoe will be a practical minimum.

Suppose a ring of metal is turned so that its internal diameter is identical with that of the drum, and a shoe cut therefrom. When this is fitted to the hook the recorder will function properly, but in general the current required will be greater than the values stated later in the paper. This is due to the fact that the shoe does not make contact over its entire undersurface, and a greater magnetomotive force is required to maintain the flux necessary to cause a pull of adequate magnitude. This difficulty is surmounted by the simple expedient of grinding in the shoe with very fine emery or carborundum paste, as used for motor-car valves. The pad (if fitted to the recorder) is removed, the spring $X_1$ released, paste is applied to the cast-iron rings, the drum revolved and a current of, say, 12 mA passed through one coil or through both in series. This operation will occupy about 15 minutes, but depends, of course, on the initial fit of the shoe. After grinding, the shoe is removed and both drum (outside the ring and within the slot) and shoe cleaned thoroughly with petrol. Before replacing the shoe, it is necessary to revolve the drum and apply, for several minutes, a rag soaked with petrol. After replacement of the shoe the same process should be continued until there are no further traces of paste visible on the rag. Prior to refitting the pad, the pull on the shoe should be tested by hand to ensure that the frictional force is sufficient to work the apparatus. For subsequent grinding operations, when the tension to bring the lever on to the back stop with a steady current is known, this force can be tested by means of spring $X_1$. When the surfaces are absolutely free from grease, the pad can be replaced.

The life of a shoe varies from 3 000 to 5 000 hours, according to its initial thickness. A number of spare shoes are supplied with each instrument. The wear on the cast-iron rings is inappreciable compared with that on the shoe. Under favourable conditions both rings and shoe become highly polished, but should a very strong marking signal be continued for some time, a brownish deposit appears. This seems to occur chiefly when the surfaces get warm.

If the recorder has been idle for some time in a humid atmosphere the sliding force between the drum and shoe is small, and it may fail to function with normal spring adjustment. After the drum has been in rotation for a few minutes, the force will increase. Under such circumstances it is advisable to detach the pad, dry it and remove the moisture from the drum with a dry cloth. In fact the best practice in humid atmospheres may be to dispense with the pad altogether, as it is sure to be hygroscopic.*

The lay-out of the siphon lever, relay contacts and attachment to the shoe and spring $X_1$ is given in Fig. 3. The silver siphon has its centre of oscillation coaxial with that of the lever, and is therefore not subjected to bending or twisting, except that due to its motion resulting mainly from the impact of the tongue on the relay contacts. The lower end of the siphon is gripped by a locking device at the extremity of the lever. It cannot, therefore, overshoot, and there is no necessity to add a damping device. Moreover, apart from atmospherics, the tape is freed from the somewhat cryptic scribing of certain forms of recorder. With large amplitudes and speeds of working greater than 150 words per minute (w.p.m.), the unsupported portion of the siphon oscillates and minute irregularities are introduced into the tape unless the siphon is held tight in the lever. In shaping the end of the siphon to an oval, a wire of the desired cross-section should be inserted and the siphon squeezed thereon.

---

* In some cases this may be due to the surfaces not fitting each other properly.

* The pad is really unessential and is not fitted in present-day instruments.

The pressure of the siphon on the paper can be adjusted by the manipulating screw C (see Fig. 1). When the bore is of suitable size the flow of ink can be regulated by varying the pressure on the paper and the opening of the hole at the top of the inkpot. It is clear that the transverse motion of the siphon will be impeded if the paper pressure is excessive, thus producing badly formed characters, i.e. augmenting the transit time of the lever. To obviate excessive paper friction the siphon lever must bend readily in a vertical plane.

### (3) Single-Current Working.

When the recorder is operated from a relay, and single-current working is used, the connections are as shown in Fig. 4. The battery voltage for speeds of 150 w.p.m. should lie between 70 and 100, and for 250 w.p.m. the latter figure should be increased to 150 or 200. The shunted-condenser combination CR ensures that the rate of current-rise is rapid. The most important factors are the rates of growth and decay of the current, the values of which should be as large as possible. Owing to the comparatively large inductance of the signal coil, the high voltage and the CR combination are essential for speeds of 50 w.p.m. and upwards.

The inductance of the drum as measured at a frequency of 100 periods per sec. is given in Table 1.

Table 1.

*Inductance of Recorder Coils at* $f = 100 \sim$ *and R.M.S. Ampere-turns* $= 40$.
*Lowmoor iron shoe* $\frac{3}{32}$ *in. thick.*

| No. of turns on coil | Resistance (48 s.s.c.) | Inductance | |
|---|---|---|---|
| | | Shoe on | Shoe off |
| | Ohms | Henrys | Henrys |
| 500 | — | 0·16 | 0·125 |
| 1 000 | — | 0·65 | 0·5 |
| 2 000 * | 1 900 (outer coil) | 2·6 | 2·0 |
| 4 000 | — | 10·4 | 8·0 |
| 8 000 | — | 41·6 | 32·8 |

Referring to Fig. 4, when T and S make contact and $CR^2 = L$ the condenser voltage balances † the induced voltage due to the fall in current through the recorder. If, however, the condenser is made much larger than the value obtained from the formula $CR^2 = L$,‡ it discharges through the recorder and annuls the magnetization rapidly.§ The coefficients of the circuit are such that the discharge would be oscillatory, if the inductance were constant and had the same value as in Table 1; the frequency of the oscillations and the damping should be as large as possible. By increasing $C$ sufficiently and adjusting the speed of transmission to a suitable value, double dots can be obtained (see Fig. 22, No. 3). With speeds up to 120 w.p.m. there are wide limits for $C$ and $R$. With a battery of 100 volts, suitable values are $R = 25\,000$ ohms and $C = 0{\cdot}5\,\mu\text{F}$ for a coil of 8 000 turns, whilst for a coil of 4 000 turns the values are $R = 20\,000$ ohms and $C = 1\,\mu\text{F}$ (see Figs. 27 to 31).

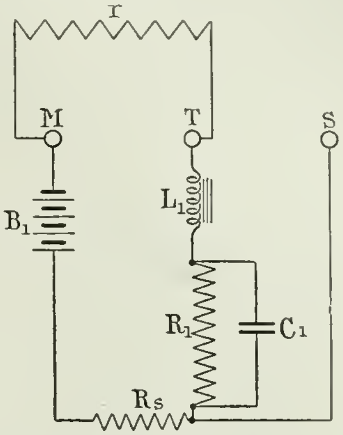


Fig. 4.—Recorder circuit for working single current from a relay using a back contact.

M = marking contact.
T = tongue.
S = spacing contact.
$C_1R_1$ = shunted condenser combination.
$R_1$ = 25 000 to 30 000 ohms.
$C_1$ = 0·5 $\mu$F.
$B_1$ = 100 volts.
r = resistance to prevent sparking at contacts, 40 000 to 60 000 ohms (use optional).
$R_S$ = safety resistance to prevent battery being short-circuited through contacts.

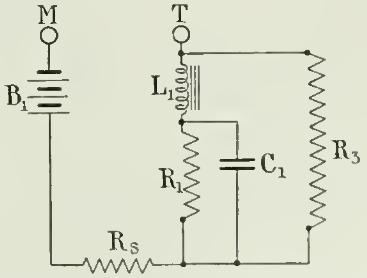


Fig. 5.—Recorder circuit for working single current from a relay using only one pair of contacts.

$C_1$, $R_1$, $B_1$ as in Fig. 1. $R_3$ = 10 000 to 30 000 ohms (to enable $C_1$ to discharge through the recorder when the contacts open).

An alternative circuit in which there is no back contact is shown in Fig. 5. The condenser discharge in this case takes place through a resistance $R_3$, the value of which can be found by trial. When using this circuit it is preferable to employ two coils, each having its own CR unit, as shown in Fig. 25. Any value of $R_3$ between 5 000 and 15 000 ohms would be

---

[*] This row of figures was obtained by measurement, the remainder by calculation, assuming $L \propto n^2$. The inductance varies with current and frequency, and these figures are quoted merely to indicate the order of magnitude under specified conditions.

[†] Assuming $L$ to be unvarying, which is far from true in practice.

[‡] Say $CR^2 = 10L$.

[§] The eddy currents in the metal masses delay the fall in flux.

suitable. Up to 120 w.p.m. neither the back stop nor the resistance $R_3$ is absolutely essential provided the applied voltage is adequate, unless relaying is being conducted, and any tendency to heavy marking can be corrected by increasing the tension of spring $X_1$ (see Fig. 22, No. 5). Under such conditions the return of the siphon point to the base line can be facilitated by passing a current through one of the coils, of sufficient value to overcome the coercive force of the drum. This eliminates the magnetic force between the shoe and drum on cessation of the signal current. It will be shown later, however, that this is not the only thing with which it is necessary to deal.

So far as the magnitude of the current is concerned, there is considerable latitude. The pull on the lever increases with the current, as shown in Fig. 33, but there is no gain in increasing the current beyond an adequate working value. The controlling factor for a drum and shoe of prescribed dimensions is ampere-turns: 25 ampere-turns is usually adequate for any speed up to 250 w.p.m., and a smaller value can be used for lower speeds.

The number of turns on the signal coil depends on (*a*) the speed of working, (*b*) the current and (*c*) the voltage. A coil of 4 000 turns is satisfactory for all commercial speeds, provided an adequate voltage is applied. With a coil of, say, 15 000 turns of 48 S.W.G. enamelled wire, the voltage would have to be increased considerably above 100 to obtain a satisfactory record at 200 w.p.m. At 100 w.p.m. a good tape with characteristic rectangular profile would be secured with about 0·6 mA, i.e. 9 ampere-turns. With 8 000 turns the current would obviously be about 1·1 mA. If the contact area of the shoe were increased, the current could be decreased accordingly (see Appendix I). In the present instrument the maximum number of turns of 48 S.W.G. single silk-covered wire (enamelled wire of this gauge is unsatisfactory) which can be wound is 8 000. For two coils it is convenient to have either 6 000 and 2 000 turns, respectively, or 4 000 and 4 000. A barrel switch can be fixed to the base of the apparatus, by means of which the two coils can be used separately in series or in parallel, but it is not usual to do this. By re-designing the drum, coils having greater numbers of turns could be wound, but the size shown in the figure has given every satisfaction.

The foregoing values of current are given on the assumption that the shoe fits the drum properly, thus leaving no air-gap, the drum is free from grease or moisture and the alignment is good. In practice when a back spring is used the steady pull with a steel shoe may be varied between 1 lb. and 4 lb., according to the current and the state of the surface. Assuming the spring tension to be half the pull on the shoe, the steady net working force will vary between $\frac{1}{2}$ lb. and 2 lb. Since the moment of inertia of the moving parts is extremely small, the acceleration of the tracing point of the siphon is very large, the transit time (time to travel between stops) for an amplitude of 0·06 in. on the tape being about 1/700 sec. By suitable design this time can be reduced to about 1/1 200 sec. The ratio of the siphon lever arms is 4/1, the object being to prevent excessive motion of the shoe, since this has the greater mass [see Dynamic Theory (page 923)].

The marking and spacing are controlled by the adjusting spring $X_1$, and there is a great deal of latitude therein. The marking can be varied from blurring to a state where the dots become quite peaked. Once the spring is set for, say, 200 w.p.m., no adjustment is required for a lower speed. In fact, unless it is requisite that with dots the marking and spacing should be equal for all speeds, there is practically no adjustment required from hand speed up to 250 w.p.m. If the relay contacts are used, however, some adjustment is needed above 100 w.p.m. Under such conditions the gap between the contacts is made as small as convenient, so that the duration on each stop is as large as possible. With a voltage of 100, satisfactory relaying can be obtained up to 150 w.p.m. with an amplitude of $\frac{1}{16}$ in. to $\frac{3}{32}$ in. showing on the tape. For higher speeds a greater voltage or a smaller amplitude or both are essential (see Figs. 21 and 22).

### (4) DOUBLE-CURRENT WORKING.

For double-current working the circuit of Fig. 6 is used. One coil of the recorder carries the signal current, whilst the other coil is connected to a battery $B_2$ and rheostat $R_2$. The superposition of the signal current on that from the battery is either to augment or decrease the effective ampere-turns. For marking, the ampere-turns add, and for spacing they subtract. On spacing, spring $X_1$ pulls the lever mechanism on to the back stop S (Fig. 1). If the battery current from $B_2$ is reversed, spacing is recorded in place of marking. For complete demagnetization of the drum, the ampere-turns on the two coils should be equal and opposite. It is possible, however, to work with widely different values of ampere-turns on the two coils. The marking and spacing on the tape can be varied either by spring $X_1$ (Fig. 1) or by means of rheostat $R_2$. Using a battery coil of 2 000 turns and a signal coil of 6 000 turns, 200 w.p.m. can be

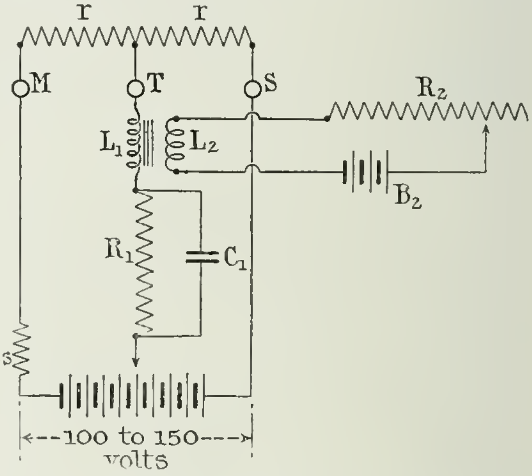


FIG. 6.—Arrangement of circuit for working double current off a relay using a back contact.

rr = resistance to eliminate sparking at contacts; 40 000 to 60 000 ohms (use is optional).

obtained with a current of 100 μA each way, the total battery voltage being 110 and the amplitude on the tape $\frac{3}{32}$ in. The resistance $R_1$ is about 500 000 ohms, and $C_1 = 0{\cdot}25$ to $0{\cdot}5$ μF (see Fig. 19).

Since the current required for single working is so small, there is little to be gained—so far as radio-telegraphy is concerned—in working double current, although a smaller current is permissible, the inductance of the signal coil can be reduced, and, since the reverse current facilitates demagnetization, it is permissible to use a smaller condenser in the CR unit. For land line or cable work, double current may be advantageous, and the small amount going to line eliminates interference (inductive effects) with neighbouring systems. A double-current system, using two contacts only, is shown in Fig. 7, this being an adaptation of G. M. Wright's reverse-current valve circuit of Fig. 16. Owing to the resistance $R_2$, a higher voltage is required than that when three contacts are employed.

### (5) SPEED ATTAINMENTS.

For square signals the highest speed yet attained with a working voltage of 100 is 250 w.p.m., but this is not the limit. Quite legible records have been obtained at 650 w.p.m., but the tape does not preserve its square profile. Square signals can be obtained at 300 w.p.m. by augmenting the battery voltage and decreasing the inductance of the drum by reducing the number of turns (2 000 in this test). These figures are probably adequate for all practical purposes in radio-telegraphy for some time hence. The present design has been altered from the original, inasmuch as the shoe has been made thicker, and therefore heavier, and the siphon longer. A speed of 200 w.p.m. can be obtained readily with 100 volts, but higher speeds necessitate higher voltages to ensure a sufficiently rapid rise and fall of current.

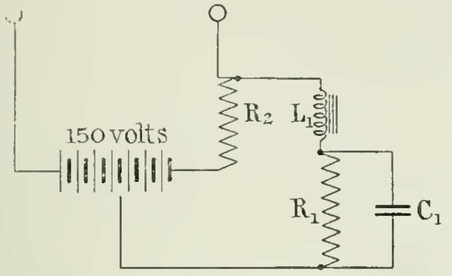


FIG. 7.—Circuit for working double current without a back contact. With the magnetic drum recorder a polarizing current must be used as shown in Fig. 6.

### (6) MISCELLANEOUS EFFECTS.

If an alternating current is supplied to the recorder, it will function in such a way that all the alternations appear above the datum line. This is due to the fact that the pull on the shoe is independent of the direction of the current. Such an effect may be designated as a form of electro-mechanical rectification. The number of alternations on the tape is halved by using a suitable polarizing current in one of the coils.

When the tongue and the contacts of the recorder are connected to a condenser-resistance unit in series with a battery and to one of the coils as shown in Fig. 8, it is possible to obtain a reaction effect. Imagine the tongue to make contact on the spacing stop. The force on the shoe due to the current in the coil will then cause the tongue to break contact and move over to the marking stop. The spring, however, pulls the siphon mechanism and tongue back to the spacing stop, and the process is repeated so long as energy is supplied from the battery. The moving system is set into rapid vibration and emits a note, the pitch of which can be varied by altering the resistance, the tension of the spring or the spacing of the contacts. The frequency varies between about 200 and 500 periods per sec. By a suitable arrangement the same effect can be obtained in double-current working.

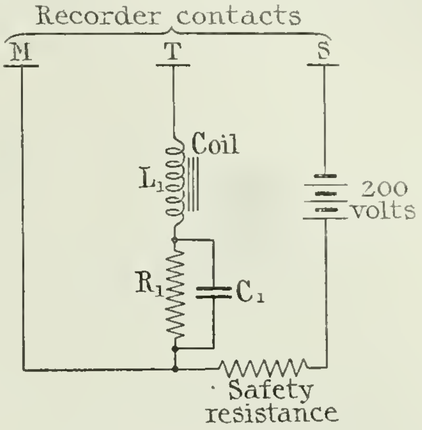


FIG. 8.—Circuit for obtaining electro-mechanical reaction.

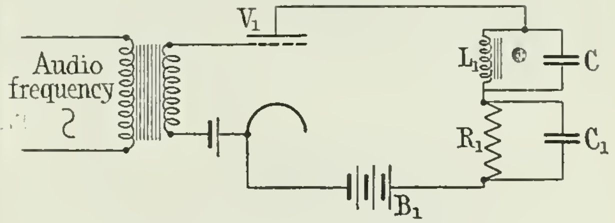


FIG. 9.—Simple recording circuit.

$V_1$ = rectifying valves in parallel.
C = smoothing condenser (about 0·5 to 1 μF) found by trial according to audio frequency.
$R_1$ = 10 000 to 20 000 ohms.
$C_1$ = 3 to 1 μF.
$B_1$ = 150 volts (or more).
A shunting resistance may be used across the recorder combination if necessary.

There is no back E.M.F. induced in the coil due to motion of the shoe on the drum, and the recorder is electrically irreversible. The only back E.M.F. is that due to inductance.

In an instrument of this class, what is required particularly is a large force resulting from a small current input. As has been shown already, this can be fulfilled most easily by working at low speeds and using a coil of many turns. For any given speed of working there is a practical limit to the force obtainable from a given input.

The various phenomena may be summed up by stating that the instrument oscillates, rectifies and amplifies. Broadly speaking, it does electro-mechanically, therefore, what a triode does electrically.

### (7) VALVE-CIRCUIT WORKING.

Since the operating current is so small, it is reasonable to suppose that the recorder will function in a valve circuit, and this assumption has been corroborated in practice. The highest speed which has been tried on actual traffic is 100 w.p.m., but this is by no means the limit, and records have been secured at 400 w.p.m. in the laboratory. Up to 50 w.p.m. almost any of the usual recording valve circuits are applicable, but for speeds in excess of this figure the circuit requires careful choice.

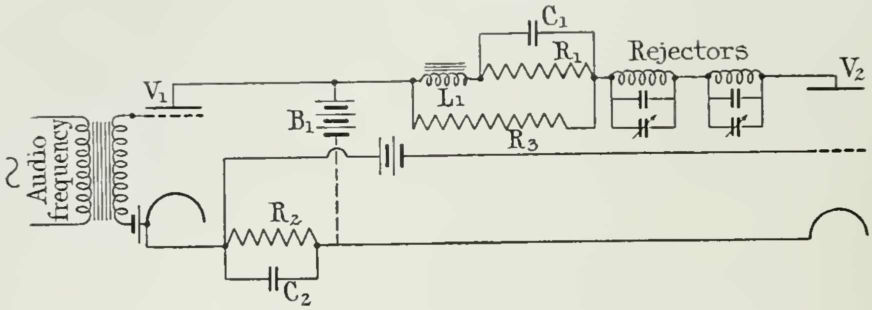


FIG. 10.—Recording circuit in which alternating current is eliminated.

$V_1$ = rectifying valves.
$V_2$ = recording valves in parallel ($V_{24}$'s or 1 radiotron).
$R_1$ = 10 000 to 20 000 ohms.
$C_1$ = 3 to 1 μF.
$C_2$ = 0·01 μF variable (found by trial according to audio frequency).
$R_2$ = 50 000 to 100 000 ohms.
$R_3$ = 10 000 ohms.
$B_1$ = 150 volts (or more).
Rejector units (optional) according to audio frequency (800 ∼ to 2 500 ∼).

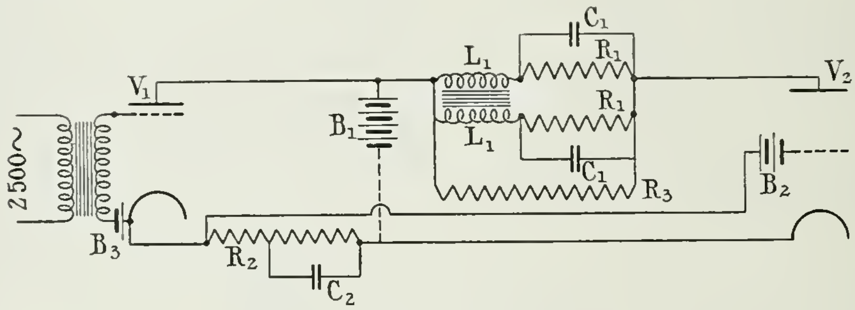


FIG. 11.

*Using 2 coils.*

$V_1$ = 1 $V_{24}$ or an R valve.
$V_2$ = 1 radiotron valve ($LS_4$).
$R_1$ = 30 000 ohms.
$C_1$ = 1 μF.
$C_2$ = 0·01 μF.
$R_2$ = (50 000 + 50 000) ohms, or 100 000 ohms.
$R_3$ = 4 000 ohms.
$B_1$ = 150 to 200 volts.
$B_2$ = − 40 to − 50 volts.
$B_3$ = − 20 to − 30 volts.
$L_1$ = 4 000 turns per coil.

*Using 1 coil.*

$R_1$ = 20 000 ohms.
$C_1$ = 1 μF.
$C_2$ = 0·01 μF.
$R_2$ = 100 000 ohms.
$R_3$ = 12 000 ohms.
$B_1$ = 200 volts.
$L_1$ = 4 000 turns.
Current through coil = 4 mA.

Signal current on dash and for working at 100 w.p.m. = 1 mA in each coil as a minimum, usually about 2 mA in practice. Rejector circuits were not used. Signal voltage applied to grid of $V_2$ on long dash = 40 to 80 volts across the terminals of $R_2$. A beat note of from 800 ∼ to 5 000 ∼ is suitable. With the apparatus used, 2 500 ∼ gave maximum signal strength. Using 200 volts this circuit is highly satisfactory for all commercial speeds of working.

In general, the resistance of a valve is comparatively high, and a large proportion of the battery voltage during the conductive periods will therefore be allotted to the valve. Thus, in order to secure an adequate voltage-drop across the recorder when placed in a valve circuit, it is essential to increase the battery voltage, to connect several valves in parallel, or to use a single valve * of low resistance and small *m* value. Where condensers are coupled in series with the valve, the resistance of the latter should be small to facilitate charging, so that the initial current peak through the recorder is obtained. It is also advisable to reduce the number of turns on the drum, thus lessening the inductance.† In order to cope with the inductive back E.M.F. of the recorder on cessation of the current, the magnification factor of the valve should be large to avoid the use of too much negative potential on the grid, thereby necessitating an increase in signal strength. This, however, is not of vital importance where a shunting resistance is used as shown in Fig. 10. In practice a compromise must be made between these two opposing conditions.

---

* A radiotron manufactured by the M.O.V. Co.

† The number of turns should be from 2 500 to 4 000. The data appended to the valve-circuit diagrams apply in some cases to a coil of 6 000 and in others to one of 4 000 turns.

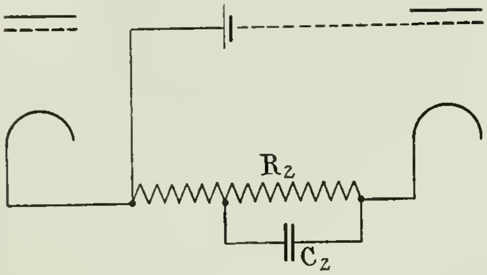


FIG. 12.—Alternative arrangement of smoothing condenser for Fig. 10.

$C_2$ = smoothing condenser.

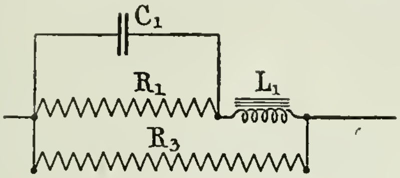


FIG. 13.—Recorder unit.

$L_1$ = recorder.
$C_1R_1$ = shunted condenser combination.
$R_3$ = resistance to permit condenser discharge through $L_1$.

The usual recorder part of the valve circuit is shown in Fig. 9, where $V_1$ represents one or more rectifying valves in parallel, such that the equivalent resistance * is not greater than, say, 2 000 to 5 000 ohms. B is the anode battery † the voltage of which ranges from 150 to 200, preferably the latter. The current in this circuit can be analysed into a steady component and an alternating component of audio-frequency with its family of harmonics. It is essential to smooth out the alternating current as far as possible, and for this reason the recorder is shunted by condenser C. An arrangement of this nature is satisfactory for reception up to 50 w.p.m., but for speeds in excess of this figure it is beneficial, but not imperative, to prevent alternating current from passing through the recorder. The alternating current should at least be reduced to a minimum. With this end in view a circuit constituted on the lines indicated in Fig. 10 can be employed. Here $V_1$ is a rectifying valve in whose anode circuit is situated a condenser-resistance unit $C_2R_2$, the extremities of $R_2$ being led to the grid and filament of a valve $V_2$. It is to be understood that in general a plurality of valves *may* be requisite for the recorder unit in order to reduce the resistance (but see Fig. 11). The recorder with shunted condenser $C_1R_1$ and resistance $R_3$ is connected in the anode circuit of $V_2$ together with several rejector units of low resistance and low inductance. These latter are tuned when a telephone is connected across the recorder or other appropriate place, until the a.c. components become practically inaudible. The condenser $C_2$ acts materially in the smoothing of the a.c. components, and this makes the work of the rejectors much more facile. It may be beneficial at the higher speeds to replace this by the arrangement shown in Fig. 12, where a part only of the resistance is shunted by the condenser. Good results have been secured with the circuit Fig. 10 up to 80 w.p.m., but for higher speeds the arrangement of Fig. 11 is useful to reduce the effect of transients due to the condenser combinations. The beat note may be varied from 800 to 5 000 periods per sec. and probably higher.

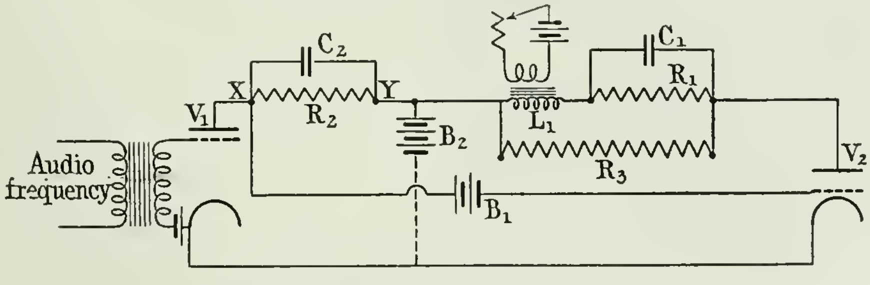


FIG. 14.—Recording circuit.

$V_1$ = rectifier.
$V_2$ = several recording valves in parallel, or one suitable valve.
$R_1$ = 10 000 to 20 000 ohms.
$C_1$ = 3 to 1 $\mu$F.
$R_2$ = 60 000 ohms.
$C_2$ = 0·005 $\mu$F (variable)
$R_3$ = 10 000 ohms (approx.).
$B_2$ = 150 volts.
Rejector units optional.

Referring to the circuit of valve $V_2$ in Fig. 10—the recorder unit is shown in Fig. 13—the arrangement necessitates the use of one coil (or two in series) only. The values of $C_1R_1$ and $R_3$ are best obtained by experiment. $R_1$ is usually from 10 000 to 20 000 ohms, $C_1$ from 3 to 1 $\mu$F and $R_3$ from 10 000 to 20 000 ohms for a coil of 4 000 turns. The function of $R_3$ is to permit the discharge of $C_1$ through the recorder on the termination of the signal. This causes a rapid annulment of the magnetization and allows the spring tension to be lessened, thus leaving a greater net force on the siphon mechanism. In using shunted-condenser units care must be taken to ensure a small time-constant value *CR*, or transients which may mar the formation of the characters will be superimposed on the signals. If it is desired to record spacing as an alternative to marking, one of the recorder coils is connected to a battery and a rheostat, the other being in the valve circuit.

---

* Let $V$ = voltage, $R$ = resistance of recorder unit, $R_e$ = equivalent resistance of valve, $I$ = mean current on a long dash; then $R_e = (V - RI)/I = V/I - R$.

† In practice it is preferable to use a d.c. machine shunted by a fairly large condenser, say of 4 $\mu$F.

To cope with speeds in excess of 50 w.p.m. the valve circuits illustrated in Figs. 14 and 15 will also be found useful. In Fig. 14 the signal of audio frequency is applied to the grid of a rectifying valve $V_1$ via a transformer. In the anode circuit of $V_2$ there is a condenser-resistance unit $C_2R_2$, one end being connected via a battery $B_1$ to the grid of valve $V_2$. The recorder and accessory apparatus are situated in the anode circuit of valve $V_2$. Both valves are worked off common filament and anode batteries. When there are no signals no current flows through resistance $R_2$, and the battery $B_1$ is adjusted so that the current flowing through $V_2$ is practically the saturation value, i.e. the valve is acting in the neighbourhood of its upper rectifying point. On the arrival of a signal the point X becomes negative with respect to Y. Since X and Y are connected to the grid and filament, respectively, of $V_2$ it follows that the current through $V_2$ decreases. Conditions should be such that the signals cause the current through $V_2$ to fall from the upper to the lower rectifying point, i.e. complete cut-off.

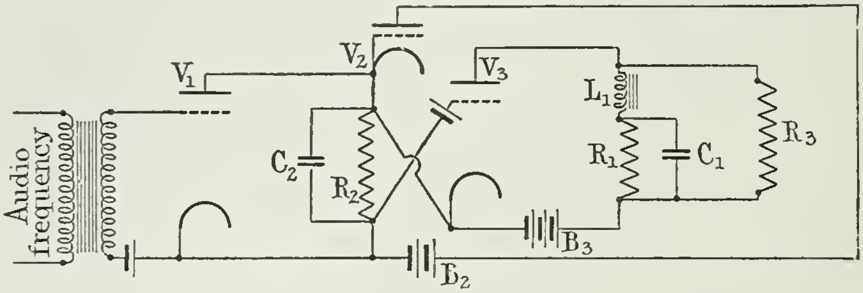


FIG. 15.—Recording circuit.

$V_1$ = rectifier ($V_{24}$).
$V_2$ = variable-resistance valve ($V_{24}$).
$V_3$ = recording valves ($V_{24}$'s).
$R_1$ = 10 000 to 20 000 obms.
$C_1$ = 3 to 1 μF.
$R_2$ = 60 000 ohms.
$C_2$ = 0·01 (found by experiment).
$R_3$ = 10 000 obms.
$B_2$ = 130 volts (or more).
$B_3$ = 150 volts (or more).

Rejectors may be inserted in anode circuit of $V_3$.

Owing to the passage of current through the recorder during spacing, and its cessation during marking, the spacing is recorded, i.e. the tape is reversed. In order to rectify this, one of the recorder coils is connected to a battery and rheostat, the magnitude and direction of the current being adjusted accordingly.

The results are satisfactory provided valve $V_2$ cuts off properly, i.e. works between its upper and lower rectifying points. Should the signal intensity decrease to such an extent that the lower rectifying point is not attained, the polarizing current in the coil is of incorrect value and the marking will be light. To avoid this the valve $V_2$ should be adjusted to cut off at the minimum signal strength. An increase will then be ineffective in altering the marking.

The second, or alternative, arrangement is illustrated in Fig. 15. In the anode circuit of the rectifying valve $V_1$ is connected a condenser-resistance unit $C_2R_2$, the extremities of which are taken to the grid and filament of valve $V_3$. To the grid is connected the positive of a dry battery of suitable voltage. At the upper end of $R_2$ is also connected the filament and grid of a valve $V_2$, the anode of which goes to a battery $B_2$, the negative terminal of the latter being joined to the filament of $V_1$. The function of $V_2$ is to act as a resistance, and by varying the filament brightness of $V_2$ its resistance can be adjusted to a suitable magnitude.

The anode circuit of valve $V_3$ consists of the recorder and accessories, with the usual battery or suitable d.c. generator. In the absence of signals, $V_1$ is non-conducting and current flows through $V_2$ and $R_2$. The P.D. across $R_2$ is such as to make the grid of $V_3$ negative to the filament. To get the necessary potential relation, the positive terminal of a battery is connected from the lower end of $R_2$ to the grid, and there should then be no current through $V_3$. On the arrival of signals $V_1$ becomes conductive every half period, and, if the resistance of $V_2$ is of appropriate magnitude compared with that of $V_1$ and $R_2$, $V_1$ will act as a shunt on $R_2$ and the current through the latter will decrease. Moreover, the P.D. across $R_2$ will suffer reduction and the grid of $V_3$ become more positive with regard to its filament. It follows, therefore, that $V_3$ becomes conductive and a current flows through the recorder and actuates it. The function of $C_2$ is to smooth out the alternating current, and, if it is desired to eliminate alternating current from the recorder, rejectors should be employed. In order to minimize inductive and resistive effects in the rejectors, the tuning condensers

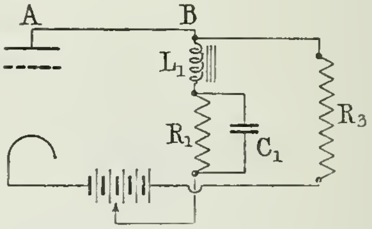


FIG. 16.—Arrangement of recording circuit for obtaining reverse current (cf. Fig. 7). With the magnetic drum recorder a polarizing current must be used as shown in Fig. 6.

A shunting resistance may be connected across the recorder unit if necessary, and a rejector circuit may be inserted in AB if necessary.

should be large, and the coils of small inductance and resistance. This prevents undue d.c. voltage-drop in the rejectors and allows it to be more efficiently proportioned in the circuit. A point of practical importance in the manipulation of these valve circuits is the filament current. Since this controls the resistance of the valve—for definite anode and grid voltages—its value should be carefully adjusted.

The circuits outlined above are specifically for single-current working. If it is desired to operate with reverse current (double working) the necessary modification can be effected by connecting one end of $C_1R_1$ to some intermediate point on the anode battery of the last bank of valves. This adaptation will be clear on inspection of Figs. 7 and 16. The circuits of Figs. 17 and 18 are also suitable for double-current working. Such circuits cope well with the demagnetization effect requisite for quick return to the spacing stop, and are useful for the higher speeds. In all circuits above a certain speed, a plurality of coils as shown in Fig. 11 is essential unless the voltage is augmented adequately. Generally speaking, the circuit of this latter figure will be found to be satisfactory for all commercial work.

### (8) Tape Records.

Samples of tape taken under different conditions are exhibited in Figs. 19, 20, 21 and 22, the actual amplitudes being indicated thereon. These illustrate the formation of the characters under actual conditions.

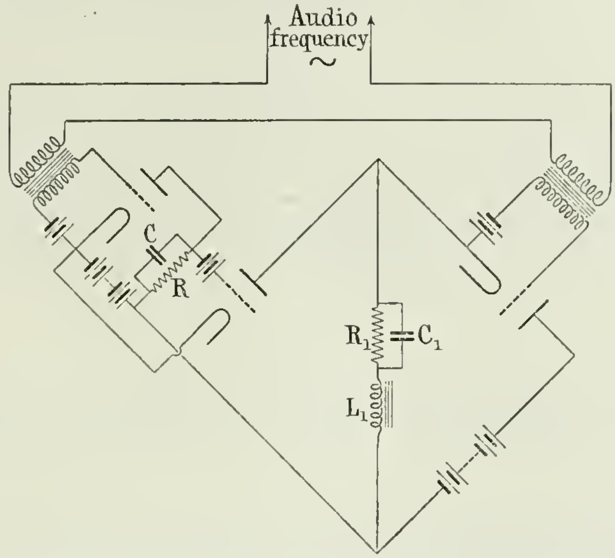


Fig. 17.

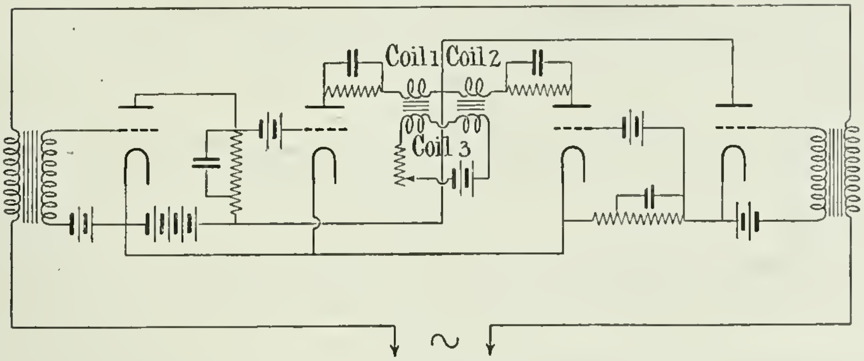


Fig. 18

Valve bridge circuits for obtaining reverse current.

The tape is difficult to reproduce. In practice the vertical strokes are quite regular. It is evident that the corners are clearly defined. The effect of making the extremity of the siphon of an oval form is to give the tape a much more finished appearance than that obtaining with a circular-ended siphon. The top and bottom strokes are thick, whilst the up and down strokes are thin, thus making the tape extremely legible and permitting economy in paper. Generally speaking, an amplitude of $\frac{1}{16}$ in. or $\frac{3}{32}$ in. can

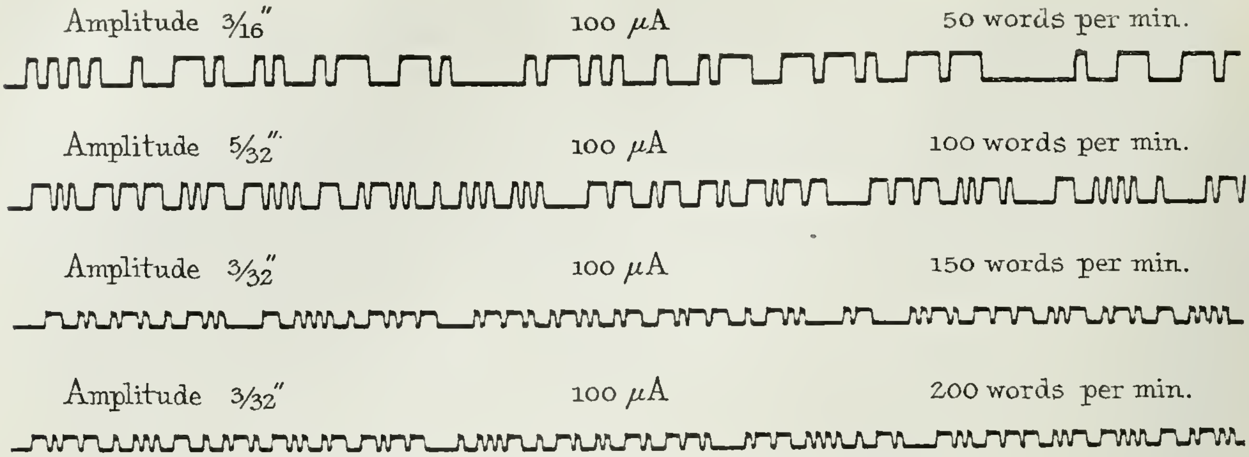


Fig. 19.—Samples of tape at various speeds on double-current working.

Turns on signal coil 6 000, on battery coil 2 000. Current in battery coil 10 mA. Voltage on signal coil 50 each way. Shunted condenser unit: $R = 500\,000$ ohms, $C = 0{\cdot}5$ μF.

Remarks: Large amplitude shows rapidity of siphon movement and curvature due to siphon lever. Large-bore siphon used. Small signal current, viz. 100 μA each way.

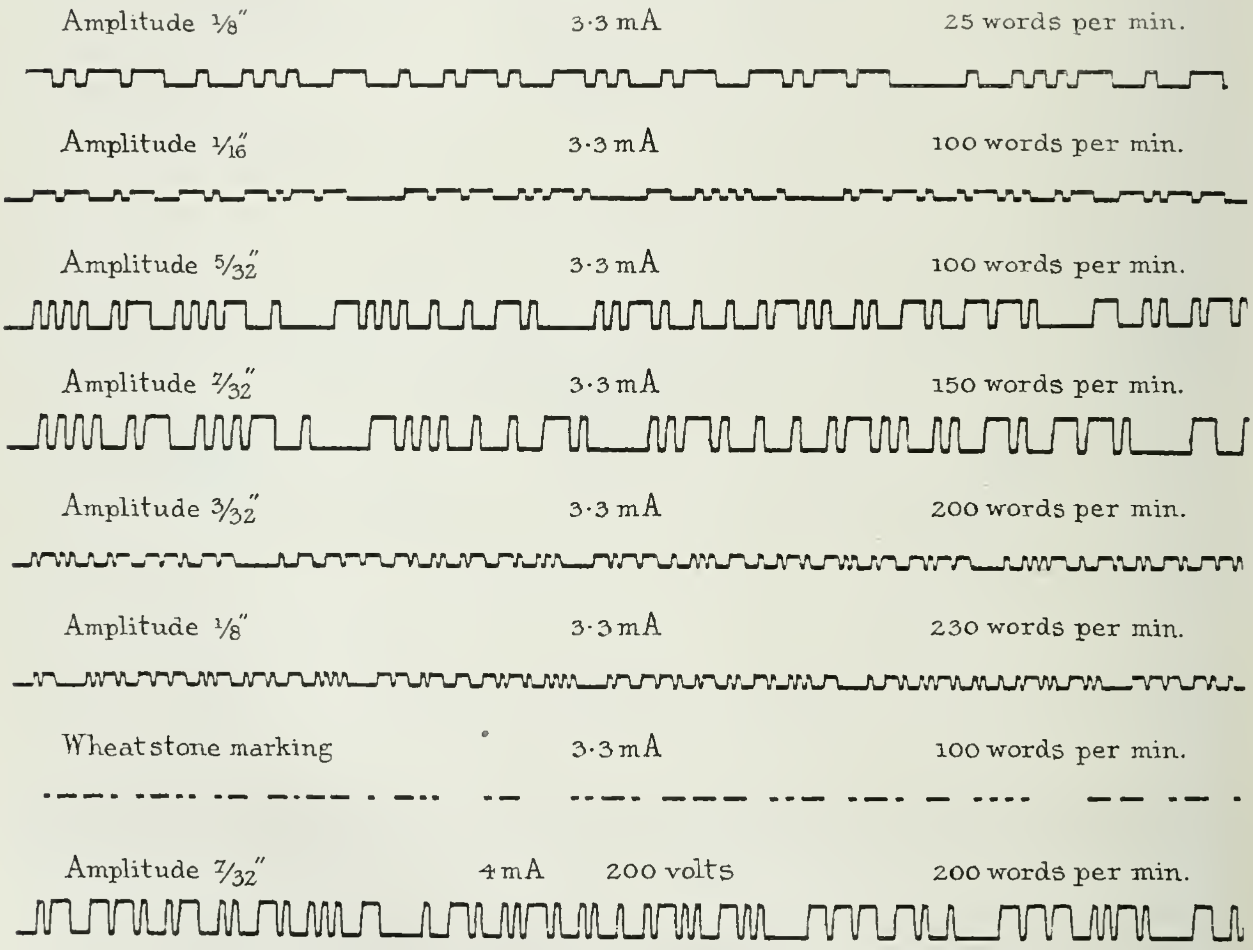


Fig. 20.—Samples of tape at various speeds on ordinary single-current working.

Turns on coil 4 000. Voltage approximately 100. Shunted condenser unit: $R = 30\,000$ ohms, $C = 0{\cdot}5$ μF.

Remarks: The 1/16 in. tape at 100 w.p.m. is given to show a useful amplitude for relaying from contacts. A speed of 200 w.p.m. with a higher voltage is shown. No adjustment was made for the different speeds, except the opening of the contacts to obtain various amplitudes.

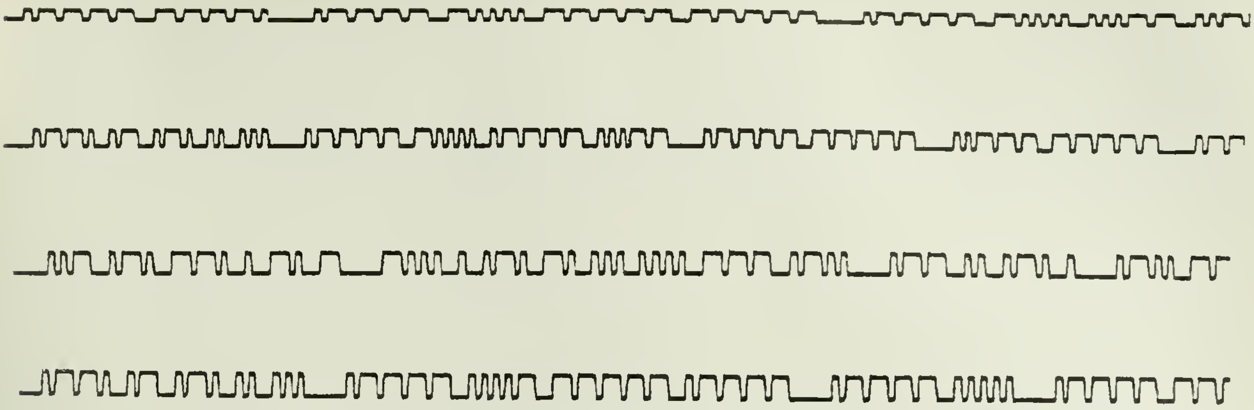


FIG. 21.—Sample of tape taken at Chelmsford from Paris U F P (Paris–Brentwood service) on 18th April, 1923.

Recorder in valve circuit, working single current. Two coils of 4 000 turns, each with its own condenser-resistance unit (30 000 ohms, 1 $\mu$F), the combination being shunted by 4 000 ohms. Current in each coil 2·5 mA. Voltage on valve circuit 200. Note frequency 2 500 ∿. Amplitudes 1/16 in., 3/32 in., 1/8 in. and 3/16 in. Speed 100 w.p.m.

Remarks: It is essential that the marking (see top line) and spacing on dots should be equal when the recorder is used for relaying to a line at the other end of which printing machines are in operation.

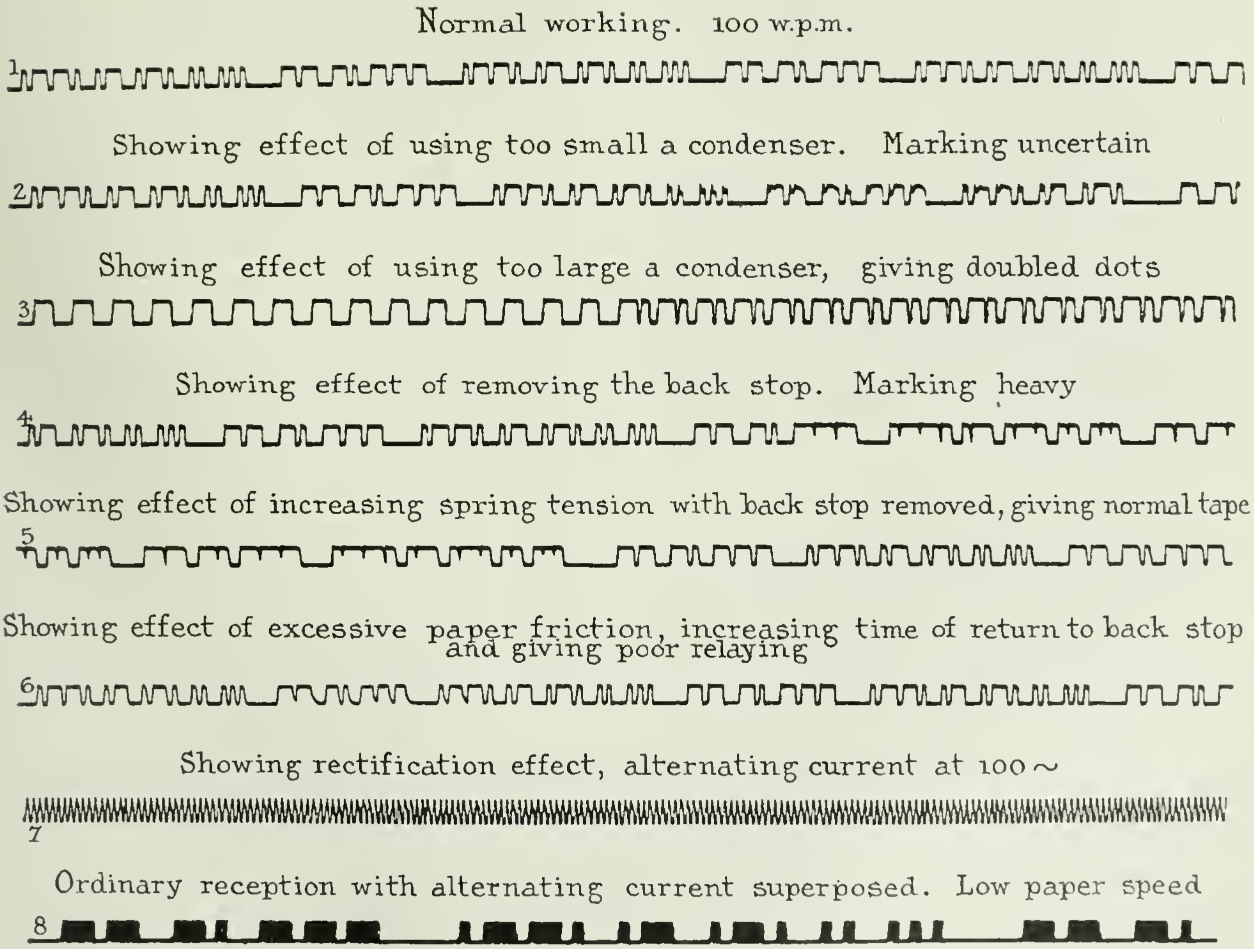

Normal working. 100 w.p.m.
1
Showing effect of using too small a condenser. Marking uncertain
2
Showing effect of using too large a condenser, giving doubled dots
3
Showing effect of removing the back stop. Marking heavy
4
Showing effect of increasing spring tension with back stop removed, giving normal tape
5
Showing effect of excessive paper friction, increasing time of return to back stop and giving poor relaying
6
Showing rectification effect, alternating current at 100 ∼
7
Ordinary reception with alternating current superposed. Low paper speed
8

FIG. 22.—Samples of tape showing miscellaneous effects.

Remarks: In cases 2, 3, 4 and 6 it is possible to rectify the defects by adjusting the spring tension, as shown in 5.

be read comfortably, and with this setting the service records are mainly obtained. Greater amplitudes are more difficult to decipher, and are shown merely with the object of illustrating the highly positive action of the apparatus, i.e. the large ratio of torque to moment of inertia or, broadly speaking, force to mass. The operative forces would give amplitudes in excess of those depicted in the reproductions, but the magnitude of these are ample for demonstration purposes.

### (9) Features of the Apparatus.

These may be summarized thus:—

(1) For a recording instrument, it is extremely robust and compact.

(2) The ratio [working torque/moment of inertia] for a given signal current is comparatively large for an electromagnetic recorder. The transit time for an amplitude of 0·06 in. is approximately $\frac{1}{700}$ sec.

(3) It is insensitive to change of speed, i.e. no adjustment is required if the speed is varied from 20 to 200 w.p.m. The initial adjustment is far from being critical.

(4) The lengths of marking and spacing can be varied over a wide range when the instrument is functioning. This is a great advantage if the transmitter is sending light or heavy characters.

(5) The marking on the tape is of rectangular formation, and is remarkably legible at all speeds.

(6) The working current is very small and the instrument will function in a valve circuit without the use of an intermediate relay. Being fitted with relay contacts the incoming wireless signals can be recorded and relayed to a land line simultaneously.

(7) The marking end of the siphon is rigid and cannot overshoot.

(8) The highest speed yet attained with a voltage of 100 is 650 w.p.m.

### (10) Transmitting Key.

The principles involved in the operation of transmitting keys are the same as those in the relays and the recorders. The only essential difference is an increase in the size of the working parts to withstand the larger forces which are operative. Thus the diameter of the drum and the dimensions of the shoe must be augmented to give a force sufficient to move the heavier contacts. In general the shoe is in sections which are linked together, and it subtends a much greater angle at the centre of the drum than in the case of the recorder. The angle of contact should not, however, be made too large.

In the early experimental work a double-drum model was made. This model is shown diagrammatically in Fig. 24.

There are two methods of operating this form of instrument:

(1) A polarizing current is passed through one coil of each drum, usually from the same source. The operating current controlled by a Wheatstone transmitter is passed through the second coil of each drum so that in one drum the magnetizing forces add, whereas in the other they annul each other. The lever therefore moves over from the spacing stop to the marking stop. If the current through the operating coils is now reversed, the lever moves over to the spacing stop, and so on.

(2) Two separate electrical circuits are used, one for each drum. One drum operates for marking and the other for spacing. This necessitates the use of a Wheatstone transmitter with upper and lower contacts, and its adjustment is by no means easy. Apart from this there is the objection that, with the double-drum method for a key, one drum is always in operation, thus causing undue wear during idle traffic periods.

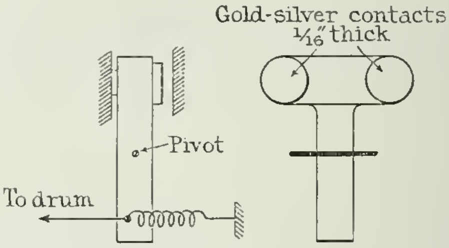


Fig. 23.—Showing lever with double contacts, thus eliminating a flexible connection secured to the lever.

A key of this nature with $\frac{3}{4}$ in. diameter contacts gave good results when worked with a double-current circuit based on that shown in Fig. 7. It has, however, little advantage over the single drum with spring pull-off, and this form has been adopted in preference.

In general the sliding force between the drum and shoe causes an appreciable rise in temperature of both parts, and there is in consequence a considerable fluctuation in this force owing partly to the fact that the radii of curvature of the surfaces are not quite equal. Another cause of this fluctuation in pull is the production of a brownish-black deposit between the two surfaces, and this may reduce the force of attraction. The remedy for these troubles is to use a small fan several inches in diameter driven direct from the motor shaft and making several thousand revolutions per minute. This cools the drum and serves to blow away most of the undesirable deposit. As an additional precaution a pad may be fitted, and this is found to cause an increase in pull. The total working force on the arm of a large transmitting key with a double-contact bridge piece, as shown in Fig. 23, is from 50 to 70 lb., the angle subtended by the shoe at the centre of the drum being 90°. The net working force is naturally less than either of these values. By passing sufficient current through the coil it is quite easy to stop a 1 b.h.p., 100-volt shunt motor, with an armature about 4 in. diameter driving through a 10/1 reduction gear, the motor normally making 2 500 r.p.m. In the key no back spring is necessary, but there is an appreciable increase in pull if a weak spring is used, due possibly to coil friction effect. There is little, if any, advantage in using this spring, since the tension of the pull-off or control spring has to be augmented accordingly.

Owing to the larger drum and shoe and the fact that the voltage is generally limited to 220, the number of turns on the drum is smaller than that on the recorder. In this way the necessary magnetizing force or ampere-turns may be obtained with a reasonable value of inductance. When the operating forces are large it has been found necessary to have a plurality of similar coils, each with its own condenser-resistance unit as shown in Fig. 25. This not only ensures a sufficiently rapid rise of current on make, but it means a reduction in the time taken for the condenser discharge current to die away when the tongue is on the spacing stop. Thus the rapid return of the key contact arm to the spacing stop is facilitated by the accelerated annulment of the eddy currents in the thick metal of the drum, which delay demagnetization.

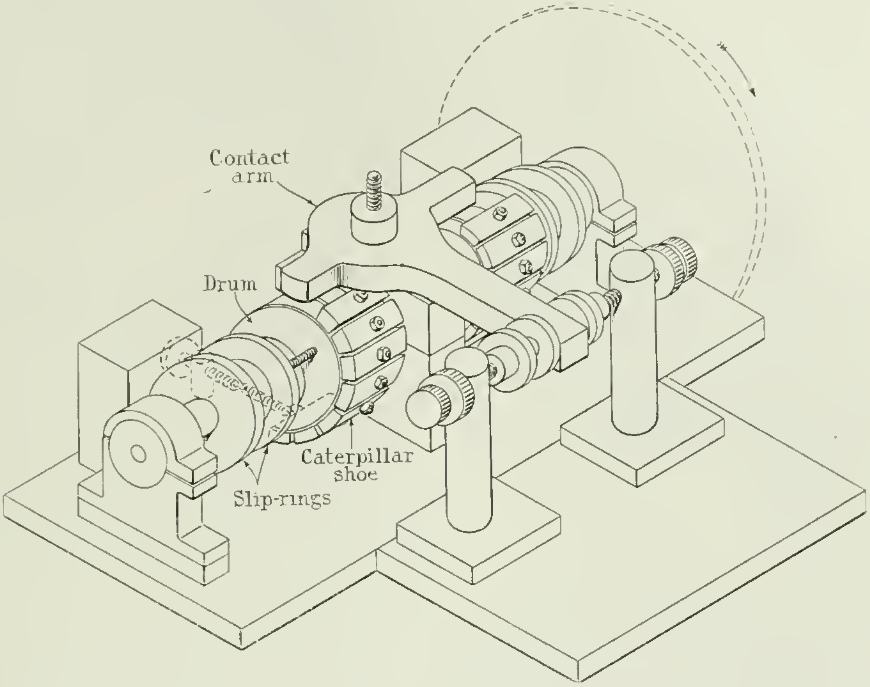


FIG. 24.—Diagrammatic representation of double-drum type of transmitting key.

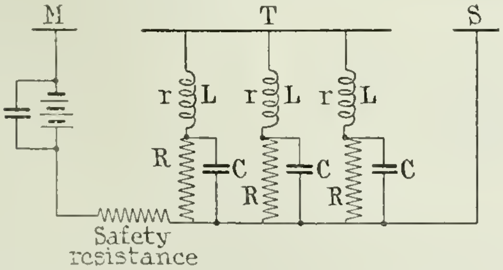


FIG. 25.—Showing plurality of equal coils on key drum, each having its own condenser unit.

### (11) TRANSIENTS AT MAKE AND BREAK.

An analysis of the transients which occur during working provides a useful guide to the mode of operation of either the recorder or a similar instrument. The circuit at make is clear from Fig. 4, whilst at break, when the tongue of the operating relay moves over to the spacing stop, the circuit is as shown in Fig. 26.

Assuming for simplicity that $L$ and the effective resistance of the coil are constant, and that the time taken for the tongue to move from marking to spacing is negligible, the equation of the transient when oscillatory is given by

$$i = \frac{V_0}{R} \, . \, e^{-kt} \, . \, \cos \omega t$$

where $i$ = current in coil at break ;

$V_0$ = initial voltage on condenser when spacing contact closes ;

$k = \frac{1}{2}\left(\frac{r_e}{L} + \frac{1}{CR}\right)$ ($r_e$ being the effective resistance of the coil, and $R$ the resistance shunted by $C$) ; and

$$\omega = \left[\frac{1}{LC}\left(1 + \frac{r_e}{R}\right) - \frac{1}{4}\left(\frac{r_e}{L} + \frac{1}{CR}\right)^2\right]^{\frac{1}{2}}$$

Since $L$ and $r_e$ are variable they affect the transients accordingly,* and the calculations using constant values of these coefficients are little or no guide to the phenomena which occur. Hence the only method of procedure is to obtain oscillograms, and using these as a guide to find the best conditions empirically.

---

* See N. W. McLACHLAN, *Philosophical Magazine*, 1921, vol. 41, p. 33.

Some typical oscillograms are shown in Figs. 27 to 31. From these and the tape obtained in practice it is found that there must be a reverse current to annul the eddy currents and the magnetization.

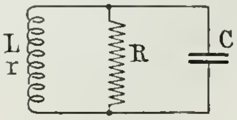


FIG. 26.—Showing circuit when tongue is on the spacing stop.

This current should be of the same order of magnitude as that at make and of short duration, i.e. rapidly damped. In order to achieve this result $C$ should not be too large, and $R$ should not be too small compared with the impedance* of the coil, which will be augmented owing to $r_e$ being much greater than its d.c. value. This permits a sufficient proportion of the condenser discharge to pass through $L$, i.e. the short-circuit and damping effects of $R$ are less. The reason for the arrangement exhibited in Fig. 25 will now be evident.

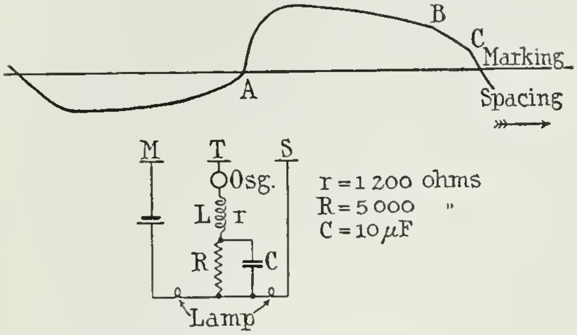


FIG. 27.—Recorder oscillogram.

Conditions: Dots at 50 w.p.m.; 220 volts; steady current = 35 mA in two coils of 4 000 turns each in parallel. Shoe on drum.

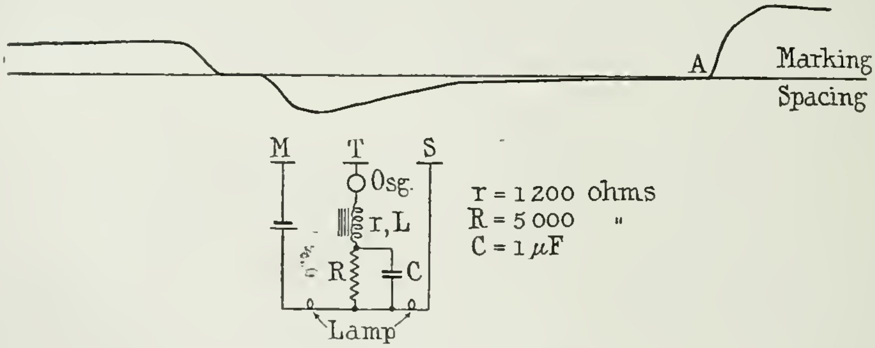


FIG. 28.—Recorder oscillogram.

Conditions: Dots at 50 w.p.m.; 110 volts; steady current = 19 mA in two coils of 4 000 turns each in parallel; shoe on drum.

### (12) OSCILLOGRAPH RECORDS.

Figs. 27 to 31 show the current through the key and through the recorder under favourable and under adverse conditions. The voltage wave is also of importance, since the flux, which governs the magnetic attraction, can be obtained therefrom, but unfortunately the oscillograph at hand was not sufficiently sensitive to secure an accurate delineation. In Fig. 27 is shown the effect of too much capacity causing a reverse current which is prolonged during spacing so that double dots occur. Fig. 28 is fairly favourable to working conditions, but the resistance across the condenser was reduced to obtain sufficient current to give a reasonable amplitude on the photograph. From Fig. 28 it will be observed that after make the condenser causes the current to shoot beyond its steady value, and that after break the current reverses and its peak value does not last long. It should be observed that these recorder oscillograms do not represent actual conditions, since the current had to be increased many-fold to operate the oscillograph.

With the transmitting key the oscillograms have the same characteristics, but, owing to the comparatively small resistance and inductance of the coil, the initial current peaks on make and break are much more marked. Fig. 30 shows a typical case which corresponds fairly well with working conditions, except that the resistance is usually 5 000 ohms. At the lower speeds of sending, the current falls during marking from its peak value to a steady value as shown in Fig. 31. This latter figure shows the effect of inserting resistance in series with the coil during spacing. Owing to the small peak value of the reverse current, this condition is unfavourable for working and the contact lever is sluggish in returning to the back stop.

One question of importance is the limit of speed, and a study of the oscillograph records will supply an answer. The condition to be fulfilled is that at high speed the transients at make or at break must be of such magnitude and duration as adequately to magnetize and demagnetize the drum with sufficient rapidity in the interval equal to the duration of a Morse dot. Generally the peak values of the currents at make and break, particularly when the coil is of small resistance, are appreciably in excess of the value given by $i = E/R$ (steady condition, see Fig. 31). Moreover, the sliding force on the drum just after make is enhanced due to this peak value, and is greater than that for the steady condition. This is particularly the case where the resistance of the magnetizing coil is small (see Figs. 30 and 31). In the absence of a marked peak value the operating steady current has to be increased. In a valve circuit, owing to the appreciable resistance of the valves, this condenser effect cannot be so pronounced, and thus the steady working current is greater than that where the operation of the instrument is controlled directly by a contact device offering negligible resistance.

---

* This is, of course, variable under working conditions.

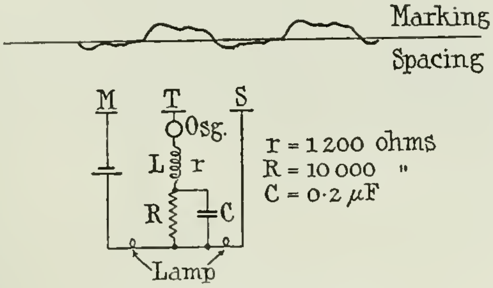


Fig. 29.—Recorder oscillogram.

Conditions: Dots at 250 w.p.m.; 220 volts; steady current = 19 mA in two coils of 4 000 turns each in parallel; shoe on drum.

It is now possible to explain why the marking and spacing can be varied between wide limits as mentioned in a previous section. Under the normal control spring adjustment the horizontal portion on the slip which indicates marking is scribed a short time after the circuit is made. The interval is attributable to the finite rate of rise of current, and to the flux lagging behind the current, variations therein being impeded by eddies. Both of these factors augment the time taken to attain a force sufficient to overcome the tension of the control spring. Thus with a large spring tension the arrival at the marking stop is delayed appreciably. Marking continues until break occurs, and when the current has fallen to a suitable value the mechanism is quickly brought back to the spacing stop under the action of the strong spring. With a small spring tension the marking stop is reached more rapidly, whilst at break the return movement is delayed until the reverse current due to the condenser discharge has reduced the magnetization of the drum to a sufficiently small value.

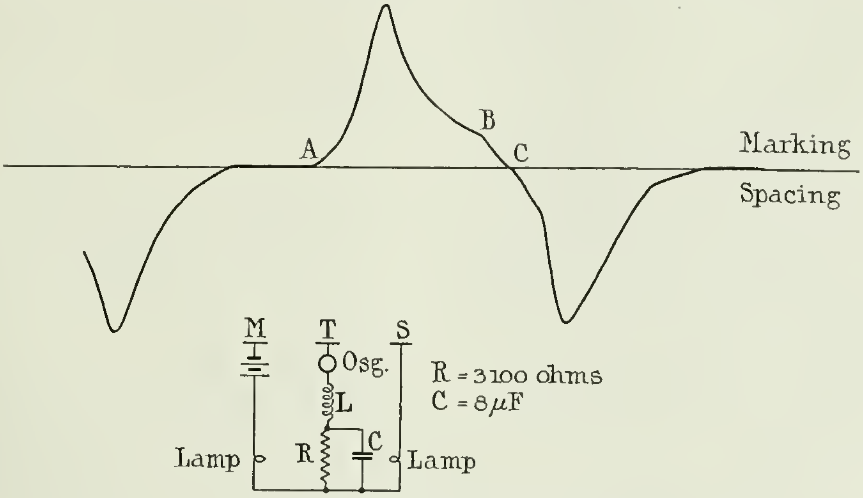


Fig. 30.—Key oscillogram.

Conditions: Dots at 100 w.p.m.; 220 volts; steady current = 72 mA in coil of 700 turns; shoe on drum.

(13) Amount of Power Controlled by a Key.

The amount of power which a key is capable of controlling depends mainly on the method used for signalling. If large currents pass through the key contacts these latter must be of appropriate diameter, and the gap or separation between the fixed and moving contacts must be large enough to prevent undue arcing, especially if break is followed by high-voltage transients. Since the circuit must be completed through the movable contact arm, it is usual to make a flexible connection between this and one of the terminals. This is, however, often a source of annoyance owing to its disintegration due to incessant vibration. A mode of overcoming this is indicated in Fig. 23, where the movable arm carries an upper and a lower contact which meet corresponding insulated contacts in a metal block fixed to the key base. The terminals are connected to these latter contacts so that the arm is merely a short-circuiting bridge, and, since there is a double gap, the amplitude of motion of the arm is about half that in the usual single-contact arrangement. To ensure that the upper and lower contacts shall both make, spring buffers are fitted to the contacts in the metal block.

Fig. 32 illustrates N. E. Davis's method of keying a valve transmitter in which the coupling coils $C_1$, $C_2$ oppose each other, this being the condition for spacing. For marking or sending, one coupling coil is short-circuited by the key. In a 30 kW set the current through the contacts might be from 200 to 300 amperes, so that a key with 1 in. diameter contacts would be required. The suppression of the arc at break can be facilitated by the adjustment of a variometer V in the anode circuit of the oscillating valve.

### (14) Sliding Force between Drum and Shoe.

A superficial way of arriving at the working force is to assume that if $\mu$ is the coefficient of friction and $f$ the pressure of the shoe on the drum due to magnetic attraction, the force necessary to cause sliding motion will be $\mu f$, $f$ being obtained from the formula

$$f = B^2A/8\pi.$$

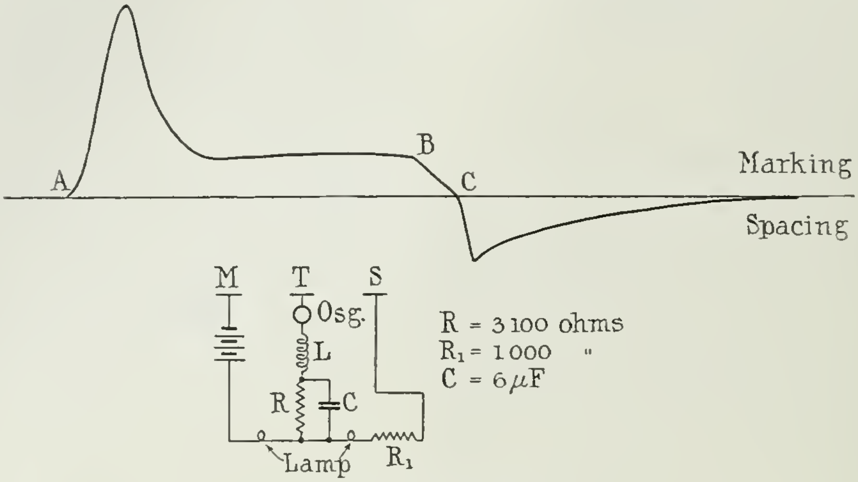


Fig. 31.—Key oscillogram.

Conditions: Dots at 50 w.p.m.; 220 volts; steady current = 70 mA in coil of 700 tu ; shoe on drum.

That this is very far from fact will now be shown in detail. In reality the action of instruments of the magnetic-drum class is dependent on some form of cohesion * between two surfaces in very intimate contact; hence the reason for extremely accurate workmanship.

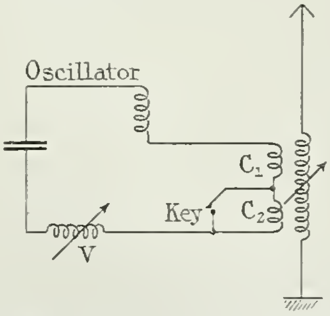


Fig. 32.—Method of keying valve transmitter by short-circuiting an opposing coupling coil.

Fig. 33 shows the relationship between ampere-turns and pull on the shoe of a recorder, also the relationship between flux density at the shoe contact and ampere-turns as obtained by experiment. From these two curves we obtain the curve shown in Fig. 34. This indicates the manner in which pull varies with flux density.

From such a curve, the formula $f = B^2A/8\pi$ (where $B$ = flux density at shoe contact assumed uniform and $A$ = total contact area), and the assumption that $\mu$ (the coefficient of friction) is $\frac{1}{3}$, a hypothetical curve is added to Fig. 34.* It will be seen that there is no agreement whatever between theory and practice, and, to emphasize this still more, another curve has been drawn showing the ratio of the two. Initially this ratio increases with increase in flux density until it attains a maximum value, then it decreases with increase in flux density, and therefore with increase in the magnetic attraction. The relationship is akin to a permeability or an asymmetrical resonance curve. It is hardly feasible that the coefficient of friction in the accepted sense of the term could be of the order of 30 and upwards.

A further experiment was made to determine the relation between the force to cause sliding and that to pull the shoe radially off the recorder drum.† Curiously enough, the ratio of the two quantities was greater than unity, its value for the recorder with the Lowmoor shoe being approximately 1·3 for a wide range of flux densities. This experiment indicates that the radial and tangential forces are of the same order of magnitude, whilst the former is many times greater than that calculated from the expression $B^2A/8\pi$. In order to investigate this problem further, a series of measurements of tangential pull and radial pressure imposed by an external load have been made for various values of the magnetizing current. A back spring was employed to steady the shoe and the cage which carried the load. The initial set of observations was taken with the back spring removed. The shoe was apt to rock about but, so far as could be ascertained, the lowest line in Fig. 35 represents approximately the relationship between tangential pull and radial pressure for zero magnetization. The slope of this line is regarded as the coefficient of friction and its value is nearly 0·6. The effect of adding the back spring is to shift this initial line vertically upwards through a distance equivalent to 0·15 lb., but the slope is unaltered. A similar result is obtained by magnetizing the drum. For the values of magnetization used in these tests the points lie approximately on a series of parallel lines, although there is a tendency to convexity upwards at the higher loads. The slope of these lines may also be regarded as the coefficient of friction, which is substantially constant. In Fig. 36 a series of curves has been plotted with data obtained from Fig. 35. Inspection of the curves will show that the vertical distance between any two of them, for a given magnetizing current, is equal to the product of the coefficient of friction and the radial pressure difference. In comparing these curves with Fig. 33 (this representing data secured under operating conditions) it must be borne in mind that the shoe was not situated at precisely the same position relative to the drum in both cases, so that the line of pull would not be quite the same; also the two sets of measurements were made at different times and the state of the cast-iron rings would probably have altered. There is, however, no momentous discrepancy. Evidently the extraordinarily large tangential or sliding force experienced when the drum and shoe are magnetized, is associated with more than mere radial pressure, as found by the expression $B^2A/8\pi$ and the coefficient of friction. In fact the tangential force exceeds the radial pressure, although it must be reiterated that to ascertain the latter requires considerable skill. There seems to be an interlocking action between the drum and shoe, but this depends upon the state of the surfaces and, although one may be inclined to associate a reduction in pull with a variation in friction, it may also be due, in addition, to separation of the parts by a thin film of foreign matter, e.g. water. The effect can hardly be explained by assuming non-uniform flux distribution at the contact. If this were so, the equivalent uniformly magnetized contact area for a mean flux density of 620 lines/cm² would be

---

* The cohesive force, if it may be so termed, is incited and stimulated by magnetism.

* It will be shown later that the coefficient of friction or ratio [pull/(mechanical radial pressure)] is apparently about twice this value.

† This experiment is rather a difficult one to perform and with the drum in motion the results are liable to variation. The value 1·3 is for the drum at rest and in motion.

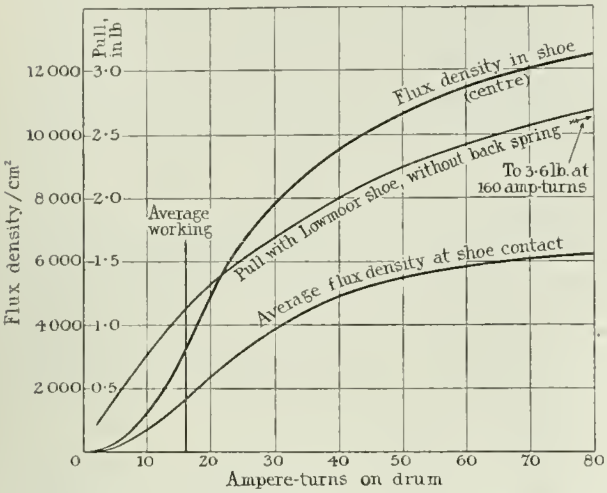


FIG. 33.—Recorder with Lowmoor iron shoe. Cross-section of shoe = 0·16 cm²; contact area = 2 × 0·32 cm².

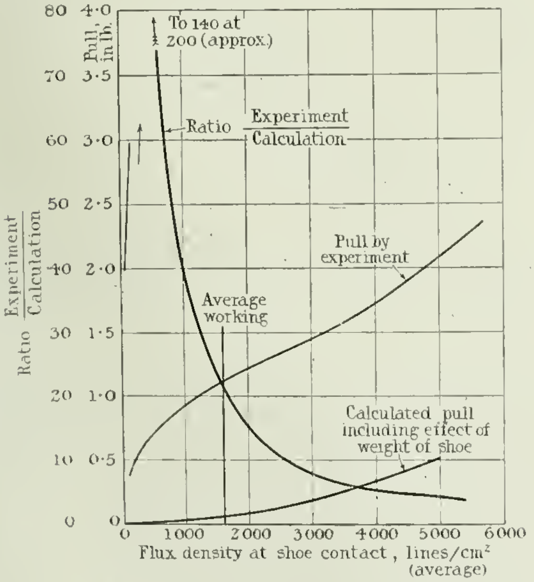


FIG. 34.—Recorder with Lowmoor iron shoe.

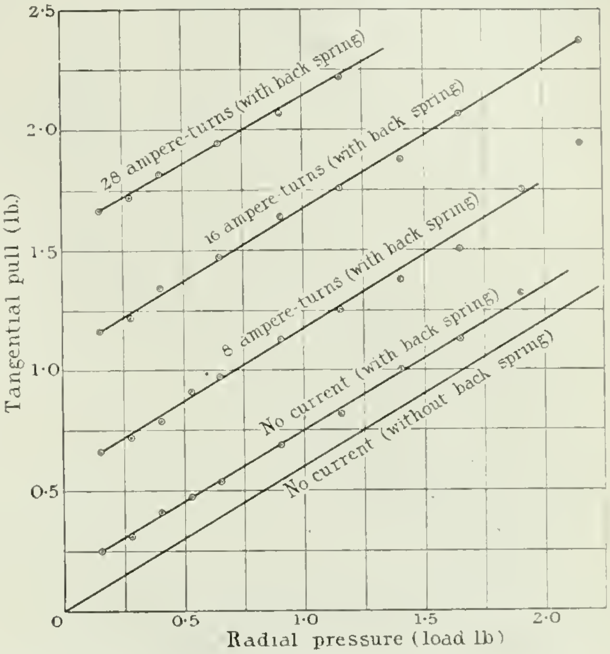


FIG. 35.—Showing relation between tangential pull or sliding force and radial pressure on the drum, due to an external load, for different values of magnetization. Recorder with Lowmoor shoe. Cross-section = 0·16 cm²; total contact area = 0·64 cm²; speed of drum = 150 r.p.m.

about 1/40th the actual area, and the equivalent flux density 25 000 lines/cm$^2$, which seems improbable owing to the large reluctance it would entail. To secure the greatest pull, the shoe must fit over its entire under surface, and this seems opposed to an appreciable variation in contact density.

As an alternative one might attribute the action to cohesion, being akin to the sticking together of two surface plates. The magnetic attraction serves to bring the surfaces of the drum and shoe sufficiently near one another to exclude air, a condition difficult to obtain between two curved surfaces by mechanical pressure.

Curves have been obtained showing the relation between pull and ampere-turns at various speeds, but the variation is more accidental than real, and for the drum speeds used on both key and recorder, viz. up to 250 r.p.m., there is no definite variation with speed.

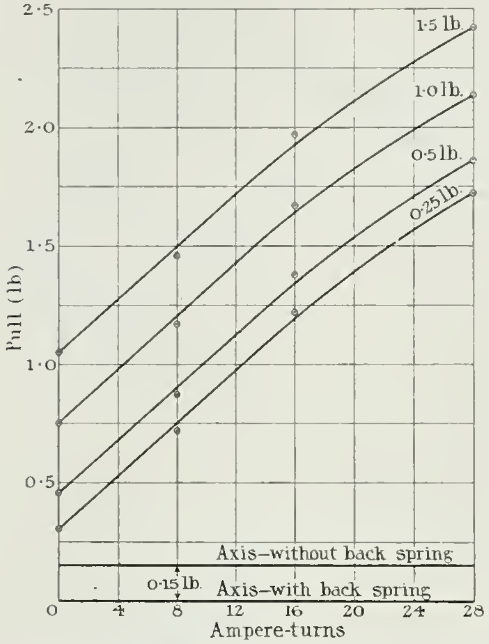


Fig. 36.—Showing relation between pull and ampere-turns for various radial pressures on drum, due to an external load. Data as in Fig. 35.

From Fig. 34 it will be seen that on the initial portion of the curve, this being the condition under which the shoe of the apparatus usually functions, it is advantageous to use a tolerably small flux density and a correspondingly large area of contact at the shoe. This yields a larger pull per ampere-turn than that for high flux density and small contact area. Furthermore, the larger contact area is conducive to prolongation of the life of the shoe and that of the cast-iron rings. In deciding the necessary contact area the shoe must not be made unduly large, since this would entail increased inertia. Provision can be made for a large area by effecting a reduction in thickness, but the limit is reached when the flux density in the cross-section of the shoe approaches the saturation value.* Taking two drums of different dimensions with shoes upon them, there does not seem to be any reason to suppose that the sliding forces are not directly proportional to the areas of contact when the flux densities there are identical, but this is not corroborated by experiment. For low flux densities the pull per unit area for a small shoe appears to be less than that for a large shoe, whilst at high flux densities the ratio $P/A$ is almost the same for large and small shoes. It depends, however, on the state of the surfaces and the fit of the shoe (see Table 2). In recording this observation it has been tacitly assumed that the two metals used are the same in all cases, i.e. cast iron on steel or cast iron on Lowmoor iron. Experiment also shows that the sliding force between cast iron and steel is greater than that for cast iron and Lowmoor iron—the shoes being the same size and the contact flux densities equal. Hence the reason for employing steel shoes for the transmitting keys, where large forces are indispensable. With the relays or recorders it is of little moment in land-line work what material is used for the shoe, but for valve-circuit work it is preferable to use steel.

In cases where the angles subtended by the shoe at the centre of the drum are different, the validity of the law of proportionality is problematic, for with large angles, owing to the rigidity of the links of the shoe, there is the possibility of the pull on the connecting rod causing increased pressure on the more remote parts of the shoe. Some data respecting this case are given in Table 2. These show the pull per unit area with one, two and three links of a three-part shoe, each link subtending an angle of approximately 30° at the centre of the drum. For small magnetizing forces (and therefore small flux densities) the larger areas show greater values of $P/A$, but there is little difference at the densities which occur in practice. Owing to the cross-sectional area of the shoe being different in the three cases, the flux densities would not be quite the same. Moreover, as a very rough working rule, it is

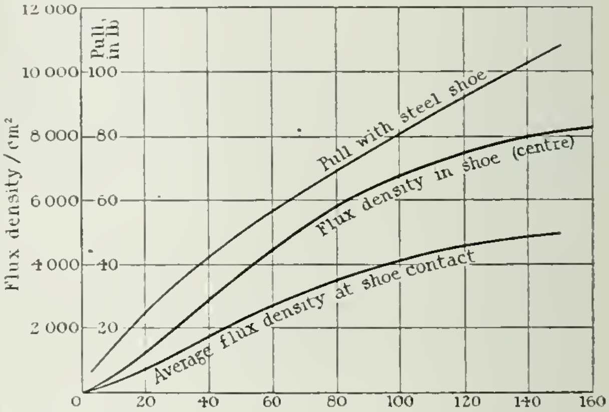


Fig. 37.—Transmitting key without back spring. Cross-section of shoe at centre = 6·1 cm$^2$ (0·75 × 8·1); contact area = 2 × 10 cm$^2$.

---

* For speeds above 100 w.p.m. the angle of contact of the shoe on the drum should not be too large.

permissible to assume that for equal flux densities at the contact such as occur in practice, and angles not exceeding 90°, the sliding force is proportional to the area of contact.

Theoretically the optimum flux density is that at which the ratio (actual pull/calculated pull) is a maximum (see Figs. 34 and 38). An inspection of the curves in these figures and a little experience will show that in practice this condition cannot always be satisfied, for owing to the steep slopes of the curves in the neighbourhood of the origin, small variations in the reluctance of the magnetic circuit due to magnetic or mechanical defects involve appreciable fluctuations in pull. Moreover, for stability, it is advisable to operate where the slope is more gradual. Thus, although the instrument will in some cases function with a very small current, care must be exercised to prevent unstable operation. In such instances a polarizing current is of assistance (see Appendix I).

TABLE 2.

*Ratio of pull/(contact area) for equal magnetizing forces and various contact areas. Steel shoe ⅜ in. thick and 1 in. wide on cast-iron rings without back spring.*

| Ampere-turns | $P/A$ ($A$ = 2·5 sq. in.) | $P/A$ ($A$ = 1·56 sq. in.) | $P/A$ ($A$ = 0·84 sq. in. |
|---|---|---|---|
| | lb./sq. in. | lb./sq. in. | lb./sq. in. |
| 11·5 | 8·4 | 6·1 | 5·4 |
| 14·5 | 10 | 7·1 | 6·6 |
| 19 | 12·4 | 9 | 8·4 |
| 22·5 | 14·4 | 12·8 | 10·9 |
| 29 | 16·8 | 16·7 | 13·3 |
| 36 | 20 | 21·2 | 19·3 |
| 57 | 26·4 | 26·9 | 27·7 |
| 107 | 43·2 | 44·9 | 41 |

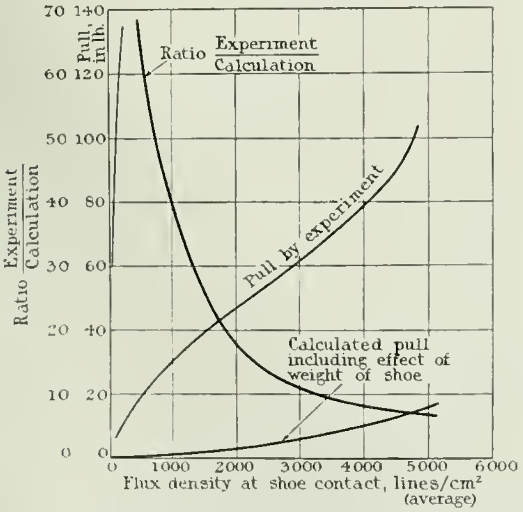


FIG. 38.—Key with steel shoe 0·75 cm thick, without back spring. Total contact area = 20 cm².

(15) DYNAMIC THEORY.

An approximate treatment of the dynamics of the recorder* type of instrument is given below :—

Let $f$ = pull on siphon mechanism due to sliding force between drum and shoe (assumed to be constant) ;
$\mathbf{I}$ = moment of inertia of complete moving system about the pivot of siphon lever ;
$r$ = distance between centre of pivot and line of pull of shoe ;
$a$ = angular acceleration of siphon lever ;
$R$ = distance from pivot to centre of siphon point ;
$f_1$ = tension of restoring spring ;
$f_2$ = equivalent force due to friction of siphon point on paper, and lever pivots assumed to act at radius $r$ ; and
$f_3$ = equivalent tension due to back spring.

Neglecting variation in tension of the restoring spring (this holds for small amplitudes) we have, starting from the back stop :—

Net or working force $f - [f_1 + f_2 - f_3] = \mathbf{I}\ddot{\theta}/r$

or $$\ddot{\theta} = f_e r/\mathbf{I} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $f_e = f - [f_1 + f_2 - f_3]$.

The linear acceleration of the siphon point is

$$a = \ddot{\theta}R = f_e rR/\mathbf{I} \quad . \quad . \quad . \quad . \quad (2)$$

and the linear velocity of the same point is

$$v = at = f_e rRt/\mathbf{I} \text{ (where } t = \text{time)} \quad . \quad . \quad (3)$$

When the moment of inertia of the siphon mechanism, the radius $R$ and the working force are fixed, there is a certain value of $r$ for which $a$ and therefore $v$ has its maximum value, i.e. the transit time is a minimum.

Let $\mathbf{I}_1$ = moment of inertia of siphon mechanism ;
$r$ = distance between pivot and line of pull ; and
$m$ = mass of shoe, etc., including equivalent mass of springs.

Then, to a first approximation :—

$$f_e r = (\mathbf{I}_1 + m\,r^2)\ddot{\theta} \quad . \quad . \quad . \quad . \quad (4)$$

or $$\ddot{\theta} = \frac{f_e r}{(\mathbf{I}_1 + mr^2)} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Therefore $$\ddot{\theta}R = a = \frac{f_e rR}{(\mathbf{I}_1 + mr^2)} \quad . \quad . \quad . \quad (6)$$

Differentiating with respect to $r$ and equating to zero we find that for the minimum transit time $\mathbf{I}_1 = mr^2$, i.e. the moment of inertia of the siphon mechanism about the pivot is equal to that of the shoe, etc. This simple condition is readily realized in the transmitting key, but with the recorder the siphon lever is made rather short in order to reduce the unsupported length of the siphon which is apt to oscillate violently at high speeds of working, due to the impact on the stops. For low speeds and quick action of the recorder, the length of the siphon could be increased with advantage.

---

* The theory applies equally to the key.

In this respect care must be taken to prevent undue friction of the siphon on the paper, since this would introduce a frictional retarding force, causing an equivalent diminution in the net working force and therefore an increase in the transit time. The relationship for minimum transit time is, however, independent of the paper friction. A similar argument applies to friction at the pivot. It is clear that for the highest speed of working, the moment of inertia of the complete system should be as small as is compatible with mechanical strength and satisfactory performance.

The weights of the moving parts for a transmitting key with a double-contact arm of the form shown in Fig. 23 are as given in Table 3.

Assuming the equivalent mass of the key mechanism concentrated at the shoe to be 350 g (0·77 lb.) and the net working force to be constant and equal to a pull of 40 lb., the acceleration of the mid-point of the contacts is approximately 5 000 feet per second per second (ft./sec./sec.), giving a transit time of 1/500 sec. for a gap of 0·125 in. Making similar assumptions respecting the recorder, the acceleration of the tracing point is approximately 5 000 ft./sec./sec., the transit time for an amplitude of 0·06 in. being 1/800 sec. In practice, however, both of these times are increased somewhat owing to the various frictional forces. In the first case the final velocity of the shoe is 3·6 ft. per sec., and in the second case 2 ft. per sec. The working peripheral velocities of the drum in both cases are less than these values in order to prevent undue wear of rings and shoes, but the range of speed for which provision is made in the apparatus is quite satisfactory for the traffic speeds used in modern radio-telegraphy.

TABLE 3.

| Item. | grams | lb. |
|---|---|---|
| Steel shoe .. .. .. .. | 168 | 0·37 |
| Keying lever with hook attachment | 165 | 0·36 |
| Duralumin arm .. .. .. | 19 | 0·042 |
| Steel link and screw for arm .. | 5 | 0·011 |
| Keying lever spring .. .. | 9 | 0·02 |
| The weights for the recorder are: | | |
| Large Lowmoor iron shoe, brass guide and screw | 4·4 | 0·0097 |
| Siphon lever, coupling hook and screw | 2·45 | 0·0054 |
| Siphon holder (on inkpot) .. | 1·05 | 0·0023 |
| Siphon tube .. .. .. | 0·2 | 0·0004 |
| Back spring .. .. .. | 0·45 | 0·001 |
| Control spring .. .. .. | 0·15 | 0·0003 |
| Brass coupling link .. .. | 0·2 | 0·0004 |

In conclusion, the author wishes to thank the Marconi Company for providing the facilities necessary to conduct the research work; also Mr. A. Gray, Joint General Manager of the Company, for his encouragement and the keen interest which he has taken in the development of the apparatus. He also desires to acknowledge his indebtedness to Mr. A. W. Langridge for co-operation in developing the valve circuits; to Mr. E. G. A. Firman for assistance in the designs; to Mr. W. E. Pannett for obtaining the pull and flux curves; to Mr. A. C. Tait for obtaining the oscillograms; to Messrs. H. Cornwell and N. Day for workmanship on the first models; and to Messrs. D. Tulloch and C. Willingham for workmanship on subsequent designs.

## APPENDIX I.

### SENSITIVITY. POLARIZED SINGLE-CURRENT WORKING.

The sensitivity figures or working currents stated in the paper are such as to provide a very wide margin of safety, and this is sound policy in commercial work to ensure a reliable service. A more concrete conception of this will be gained on reference to the data given in Fig. 33. With a current of 3 mA through a coil of 4 000 turns the steady pull is about 1 lb. Bearing in mind the extra current at make, due to the condenser, and subtracting the pull due to the control spring, the operating force is about 0·75 lb., whilst the total weight of the mechanism is barely 0·02 lb. This ensures a rapid and precise action.

The instrument detailed in the paper may be described as a "universal" one, since it works without adjustment up to 200 or more words per minute, and it is at the higher speeds that the large forces are advantageous. It is, however, a simple matter to construct an instrument for a special purpose, by merely altering the number of turns on the drum and the size of the drum and shoe. For example, if the contact area of the shoe is increased to four times its normal value and the turns are doubled, the current on single working is reduced to 0·125 of its former value, viz. 0·375 mA. Under such conditions, owing to the transients, the speed for good tape would probably be limited to 150 w.p.m. There is another method of increasing the sensitivity, which has already been cited, viz. double-current working. By using a polarizing current it is possible to operate on the steep portion of the "Pull by experiment" curve of Fig. 34. In this way the "universal" pattern recorder will work satisfactorily on 100 $\mu$A, as shown by the tape record of Fig. 19. By increasing the size of the shoe, this figure has been reduced to 25 $\mu$A at 150 w.p.m. Although this current is only 0·05 of that required for a Gulstad relay, the working forces are greater, and the instrument relays and gives a copy of what it relays. If the speed had an upper limit of 100 w.p.m., the current could probably be reduced to 10 $\mu$A by augmenting the size of the shoe and increasing the number of turns on the drum.

Turning now to the usual pattern of electromagnetic recorder, the current required to give square marking at 100 w.p.m. would be about 20 mA. This is hundreds of times greater than that required for the magnetic drum apparatus.

For sensitive single-current working, the circuit illustrated in Fig. 39 is adopted. One coil carries the signal current, whilst the second or polarizing coil is connected to a rheostat and local battery. By varying the polarizing current, the marking, spacing and sensitivity can be controlled. The current at 150 w.p.m. for an instrument with a three-part shoe of larger contact area than that on the "universal" type is 50 $\mu$A. These remarks apply specifically to working off a relay, but for valve circuit operation they are equally valid, although in general the currents are larger owing to the resistance of the valve, as explained in Section 12. In a valve circuit where the instrument performs the double function of relaying and recording, it is essential, especially if a printing machine is operated directly from the contacts, that the marking and spacing should be uniform, i.e. the dots and spaces should be of equal duration and the contact should be firm. Moreover, owing to the increased force, the larger current values are recommended. Since allowance is thus made for variation in signal strength, the desired result is attained with greater precision, and there is more latitude in the control of the marking and spacing as effected by spring $X_1$ (see Fig. 1). Owing to the *firm contact* and the small transit time, which ensures a proportionately long contact duration on the stops, the relayed tape is *identical* with the record on the instrument.

Using the circuits of Figs. 4 and 39, i.e. ordinary and polarized single-current working, it is possible to work up to speeds of 200 w.p.m. when the resistance $R_1$ is infinite. Under this condition there is no steady current, and the apparatus functions solely on the condenser charging and discharging currents. There is a lower speed limit depending on the duration of the condenser charging period, and this is about 35 w.p.m. Such an arrangement is of no commercial use in radio-telegraphy, because the lever only holds over on the marking stop for a limited time, and it would be impossible to record a long dash. With ordinary single-current working this difficulty can be surmounted by utilizing the contacts on the siphon lever to close an auxiliary circuit through the second coil, and thus supply a polarizing current as indicated in Fig. 40. During spacing there is clearly no polarizing current.

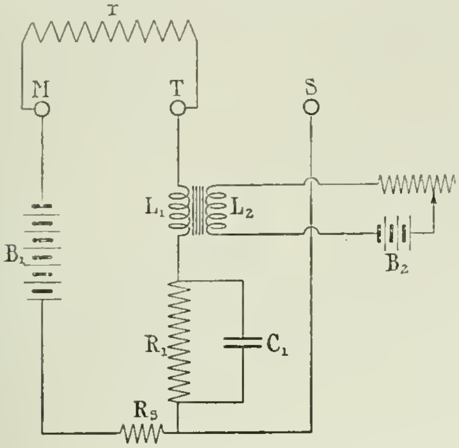


FIG 39.—Recorder circuit for polarized single-current working from a relay.

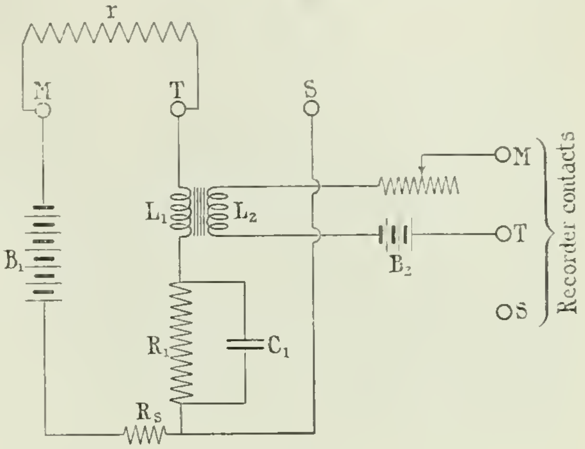


FIG. 40.

There are several points in connection with sensitivity to which we may refer. Having fixed the upper limit of speed, the greatest sensitivity may be defined in various ways according to the circuit in which the instrument is used: (1) The greatest ratio of (working torque/moment of inertia) for a given current; (2) the smallest current to give a certain ratio (working torque/moment of inertia); and (3) the smallest voltage to give a certain ratio (working torque/moment of inertia).* The data already given show that the instrument is much more sensitive than any existing form of either relay or recording device, especially if the speed does not exceed 100 to 150 w.p.m., i.e. in virtue of the new phenomenon on which the operation depends, a large force can be obtained with a current relatively very small compared with that to give an equal force on other forms of electromagnetic recorder. The lower the speed the greater the sensitivity, since the duration

TABLE 4.

*Comparison of Forces with P.O. Relay and Magnetic Drum Relay by Messrs. Elliott Bros.*

| Type of instrument | Steady current | Force to pull tongue off marking contact | Mass of moving parts | Force per unit mass | Ratio | Ratio $f_cR/I = \frac{\text{Torque}}{\text{Moment of inertia}}$ |
|---|---|---|---|---|---|---|
| | mA | lb. | lb. | | | |
| Universal magnetic drum | 4 | 1·2 | 0·012 | 100 | $\frac{100}{1}$ | $\frac{40}{1}$ |
| P.O.relay | 4 | 0·06 | 0·064 | 1 | | |

Resistance of both instruments 2 500 ohms; relay set neutral.

---

* Broadly speaking, (force/mass of moving parts). Another mode of viewing the matter is to take the ratio of force to unit current.

of the transients is such that there is no appreciable interference with the marking and spacing. From the view-point of voltage sensitivity, on polarized single-current working the instrument will function up to 130 w.p.m. on 25 volts. In fact, the voltages given in the paper are on the high side in order to provide an adequate margin.

Generally it may be stated that the speed limits mentioned are those at which the formation of the characters ceases to be rectangular, and the values given can be exceeded considerably before the tape becomes unreadable.

In order to present the preceding remarks on sensitivity in a more concrete form, the data in Table 4 have been inserted.

## APPENDIX II.

### Performance of Small Transmitting Key.

If the speed is limited to 100 w.p.m., a larger shoe may be used and the working currents reduced to about 1/3 the values given in Table 5. The sensitivity can also be increased by adopting the procedure stipulated in Appendix I. In practice, owing to the increased pull concomitant with the initial rush of current to the condenser, the net working value after deducting the tension of the control spring is about 0·75 times the figures given in Table 5. The performance of the key is shown by Table 6.

From the third column it will be seen that the key is capable of giving 100 w.p.m. on a current of 10 mA, which is less than that required for the usual type of electromagnetic recorder. By using a suitable circuit it is possible to control a 30 kW transmitter.

Table 5.

*Showing Pull on Shoe with Steady Currents. Voltage on Circuit = 200.*

| Current in each coil | Pull |
|---|---|
| mA | lb. |
| 5 | 6 |
| 10 | 11 |
| 16 | 15 |
| 25 | 18 |

Table 6.

*Performance of Small Transmitting Key.*

| Speed | Gap at contacts | Total current | Approximate working force | Ratio : Force / Mass |
|---|---|---|---|---|
| w.p.m. | in. | mA | lb. | |
| 100 | 0·22 | 50 | 13 | 87/1 |
| 100 | 0·1 | 10* | 4·5 | 30/1 |

---

* By using a larger shoe and a greater number of turns, this value can be reduced to 3 mA whilst still preserving the same working force. The key will operate satisfactorily on even smaller currents.

## Discussion before the Wireless Section, 11 April, 1923.

**Mr. A. A. Campbell Swinton :** It is of great interest to note how, in the development of radio-telegraphy, things are now being used again which have been tried and discarded in the past in other connections. For instance, possibly everyone is not aware that in the present broadcasting transmission from Marconi House no microphone is employed, speech being transmitted by means of what is practically the original Bell type of transmitter, consisting of a vibrating iron diaphragm in front of the poles of a permanent magnet with coils on it. That is what was done with the original Bell telephone, in which the transmitter and receiver were similar. This arrangement was discarded when Edison and Hughes brought out the microphone, because the original electromagnetic transmitting instrument was too weak for long-distance work. With modern methods employing valves and amplifiers, however, that did not matter; the signals can be amplified and it is found that better articulation and fewer extraneous noises are obtained with what is practically the old Bell transmitter than with the more modern microphone. Again, in this room some two or three years ago we had a very wonderful demonstration of the Johnsen and Rahbek loud-speaking instrument, which was based on an electrostatic telephone receiver similar to that originally brought out in very early days by Elisha Gray. To-night we have had a beautiful demonstration of apparatus which again is a revival of old ideas. In the *Journal of the Franklin Institute* for 1879 an instrument is described which was invented by Professor A. E. Dolbear and called a Rataphone. It was a loud-speaking telephone in which the motions of the diaphragm were controlled exactly as in the instrument now described. There was a revolving magnetic core (Dolbear did not revolve his coils, but merely the core), and on the two ends of the circular bar that was used were two iron fingers which rubbed upon the core, and the variable frictional pull vibrated the diaphragm. That instrument, as I have said, was first described in the *Journal of the Franklin Institute* in 1879, but there is also an illustrated description of it in E. Hospitalier's book on " Modern Applications of Electricity," translated into English by Dr. Julius Maier and published in 1883. Prior to that book, some 40 years or more ago I made one of these instruments myself, but I confess that it did not work well as a speaker; there was a good deal of noise, but only imperfect articulation. I should like to ask the author whether he has made any attempts to use his apparatus as a loud-speaker for telephony, or whether it has been applied only to the two instruments which he has shown to-night. I think that there are probably many other methods which were used in the early days of telegraphy and telephony and subsequently discarded, which may become useful again under the absolutely different conditions which now obtain, with thermionic valves and in connection with wireless telegraphy and telephony.

**Mr. H. Ewen:** In connection with the driving of the drum, it would be of interest if the author would give us some figures as to the relations found between the pull obtained and the speed of rotation. Some tests have apparently been made but no information is furnished. The principal point in the design of this transmitter appears to me to be the great advantage which it shows over any other type in enabling comparatively weak electrical impulses to be transformed into a very positive mechanical effort. The author has not given much information as to the performance of the instrument as a high-speed key; perhaps he will give in his reply some more data in this connection.

**Mr. R. E. H. Carpenter:** I have a very decided personal preference for recorders which give a response proportional to stimulus rather than for those of the "all or nothing" type, in which the recording mechanism works between fixed stops. It would be of considerable interest to know whether the author has worked out a proportional instrument on the principles described. A recorder the deflections of which are proportional to the operating current, used directly in suitable valve circuits, has two very great advantages where atmospherics are at all troublesome. In the first place, the atmospheric is almost always easily recognizable as such; there is no danger of it being confused for a signal, even though it obliterates a signal. Secondly, with it a great deal of visual discrimination is still possible to skilled telegraphists, enabling them to read a signal in spite of atmospheric interference which would completely block up signals on the fixed-stop instrument. On short-distance circuits, where the received signal is of ample power, this consideration may not, perhaps, be so very important; but I have found, working on transatlantic signals in New York during the summer months, when atmospheric conditions are considerably worse than anything normally experienced in this country, that while a recorder of the proportional type gave signals which experienced men could read quite easily with very few RQ's, one with fixed stops gave signals scarcely intelligible for more than a few words at a time on the tape. The great danger with all recorders working between fixed stops is that there is nothing inherent whereby we can recognize what is signal and what is atmospheric, and, where the absolutely correct reception of messages is the important factor, this, to my mind, completely rules out the fixed-stop type of recorder. The Radio Corporation of America has come to the same conclusion. In America, telegraph companies are legally responsible for financial losses arising from inaccurate messages, and I think it is a great pity that telegraph administrations in this country and in Europe generally are not in a similar position. Where a recorder is to be controlled by a relay, the danger of confusion between atmospheric and signals exists, of course, all the time; but it is frequently essential to use a relay, as, for example, when printing telegraphs are to be controlled, and it is often convenient to do so, since a well-designed relay will operate on smaller current-changes than those necessary for a direct recorder, not excepting the instruments described. It is still a great convenience, when using a relay, to have a symmetrically arranged double-current recording instrument, the zero position of the pen of which is central on the paper. With such an instrument, the adjustment of the relay for neutral bias is much easier than with the asymmetric type. When using one of the latter, a marking bias on the relay may be masked by a spacing bias on the recorder, and under these circumstances it is difficult to be sure that the printing telegraph mechanism is functioning under the best conditions. With regard to the stress laid on square signals, most practical telegraphists seem to prefer a signal that is slightly rounded. They say (and I agree with them) that a signal which is absolutely rectangular is very tiring to the eyes to read for long periods of time together, and I think that a signal can be made too square for comfortable reading. While greatly admiring the ingenuity that has been put into the design of these instruments and their associated circuits, one cannot help being struck with the number and complexity of the adjustments that apparently are necessary.

**Mr. J. Joseph:** I take it that the instrument has not yet been applied to submarine telegraphy. The current available for submarine work is, of course, very much less than is used in connection with this particular design; if one gets as much as 2 mA on a submarine circuit that is about the maximum that can be expected; it is usually less. I presume that no experiments have been carried out in this direction. With regard to thermionic recording for radio-telegraphy, we have just seen the instrument operating on the Paris circuit and I am rather surprised that such good results have been obtained. I presume that a power amplifier is being employed. The greatest change on a multi-valve instrument is usually not more than ½ mA, and these signals are certainly exceedingly good. It appears to me that the principal application of this instrument will be for radio-telegraphic circuits or for operating power circuits by means of radio signals at a distance. I should like to express my admiration for the beautiful workmanship displayed in the instrument itself. As a manufacturer, I can appreciate the difficulties of working to 0·0001 in., and I am surprised to learn that this was done in a lathe; I should have thought a grinding machine would have been more suitable. If this drum has been turned in a lathe to 0·0001 in., it must have been an exceedingly accurate machine. I should like to ask whether difficulty has not been experienced with the shoe after considerable wear. The author states that the life of the shoe is from 3 000 to 5 000 hours. That is rather more than I should have expected, and it is certainly a tribute to the excellent workmanship. In humid climates I should have thought that considerable trouble would be experienced in the contact between the shoe and the drum.

**Mr. H. B. Tilley:** With regard to the grinding of the drum mentioned by the previous speaker, I do not wish to reply for the author but at the same time it may help matters if I point out that we find it a much better proposition to turn the drums rather than grind them, especially as it is not necessary to turn to any particular diameter, the essential fact being that they have to be dead true. When grinding, the surface is a series of flats, as revealed by microscopic examination. In turning, the diameter is left as it is after turning, and the shoe is ground in afterwards to suit. The important point is to have the drum running absolutely true, otherwise trouble will occur. I should be glad if the author would state why he used Swedish iron for the spindles; one would have thought that a good quality of steel would have been better. The author states that although the pad is used for keeping the drum slightly lubricated it is perhaps better without it. If this is so, it might have been advisable to omit all mention of a pad. I note that two dissimilar metals are used, i.e. cast iron for the drum and wrought iron for the shoe. Am I to understand that this is for the purpose of avoiding abrasion? The author mentions that morganite can be used for the brushes on the slip-rings, but I should like to know what he uses on the particular instrument which he demonstrated.

**Mr. E. H. Shaughnessy:** I notice that most of the electrical circuits associated with this relay are circuits in common use in the telegraph world—the shunted condenser circuit in series with the drum relay, etc. I am puzzled, however, to know what particular advantages this type of relay possesses over the well-known relays at present in existence, such as the Gulstad relay, the Post Office standard relay or the Carpenter relay, which all work with very small currents. I have been looking for some indication of using an infinitesimal current to work at 100 words per minute, something like 10 $\mu$A. From some of the figures I note that 50 mA is required for the transmitter key at 200 words a minute, but I should like to know how much current is actually needed for working the receiving instrument itself. I notice that in one application of this instrument the author adopts the well-known Gulstad device of causing the relay to oscillate. Gulstad himself very greatly improved the sensitivity of the standard relay, or of his own, by causing it to oscillate, and he could adjust his condensers so as to cause the relay to oscillate at any particular frequency suitable for the speed at which he was going to receive. That, apparently, is another telegraphic device which is embodied in this instrument. It is very interesting to see that these devices are applied to this new instrument. It is not clear that the relay is very much more sensitive than other relays. One of the experiments performed to-night was with the siphon recorder with the siphon pressed hard on the paper. I fail to see what that had to do with the relay, inasmuch as it is in a local circuit, and this being so it does not affect the working of the relay but only that of the siphon. If one adjusts a siphon badly one expects to get correspondingly bad results, and vice versa. I should like more information as to how the instrument can be used for dealing with large powers for keying, and to know what would be the advantage of this relay for working some other local relay with heavy contacts, as compared with any standard form of relay.

**Mr. D. Murray:** The reference to tangential forces reminds me of an experiment which Mr. S. G. Brown made many years ago in connection with his submarine cable work. He arranged a rotating steel spindle and wound a cord round it several times. A slight pull on the cord by means of a thread raised a big weight. This simple device formed a mechanical magnifying relay, and it is possible by this means to raise a hundredweight by a single silk fibre. It is my impression that some of the lessons learned and methods adopted in submarine cable work might be adapted very advantageously to wireless work. There is a tendency nowadays to work too much in watertight compartments; it might be of advantage sometimes to study what others are doing.

**Major B. Binyon:** In any subject where there are alternative methods of achieving the same result the first question which springs to one's mind is the point emphasized by Mr. Shaughnessy, namely, the particular advantages possessed by the author's method. In these days when, by means of valves (given suitable conditions), signal strength may be magnified to almost any required degree, and, moreover, may be magnified proportionately, one is inclined to doubt whether the form of mechanical magnification dealt with in the paper has a great field before it, especially in view of the desirability, pointed out by Mr. Carpenter, of proportional magnification for recording; the latter can be obtained by means of valve amplifiers applied to many of the recording systems commonly employed in line and cable telegraphy.

**Major H. P. T. Lefroy:** I should like to draw attention to one fact that has not, I think, been mentioned in the discussion, namely, that this instrument appears to be the exact magnetic equivalent of the Johnsen-Rahbek "revolving electric drum" relay; there is the same motor drive, the same intense adhesion, the same shape of recorded signal, and so on. The Johnsen-Rahbek instrument and its appropriate circuits have not, I think, been worked out with the same completeness as this one, but I should like to ask the author if he has made any comparison between the two for a given strength of signals and a given number of words per minute.

**Mr. A. C. Brown:** A number of speakers have given us the impression that old ideas and methods are being revived. I, like Mr. Swinton, made one of these magnetic detectors many years ago; and there is a great resemblance between this instrument and the Johnsen-Rahbek instrument, as has been pointed out, and also between this and the Edison "motograph," which was the pioneer of all its type. This instrument, however, may be very much more sensitive than any that have preceded it, and certainly it is more beautifully made than anything I know of which has been previously used in this connection. Most of the previous makers of this class of apparatus have directed their attention principally to telephony (using the electromagnetic frictional device to vibrate a diaphragm), but in regard to telegraphy, an instrument possibly more sensitive than either was made some time ago—a rapidly revolving drum with a layer of insulation across its diameter and a stylus bearing on the drum, the movement of which is initiated by a very gentle force either way. The initial movement is magnified, apparently by the friction of the stylus on the drum, but, the drum being run by local power, that power is imparted to the cross movement and the relay is operated. The stylus is platinized, and makes contact with one or the other end of the drum across the insulation. The instrument is very sensitive indeed. As other speakers have mentioned, it would be very interesting to know what advantages the relay described in the paper possesses over others. I do not wish to imply that it does not possess an advantage; probably it does. The apparatus is very beautifully worked out, and whether or no there is a present advantage there is always great utility in providing another way to do that which has been done before, possibly not so well.

**Mr. Ben Davies** (*communicated*): The instrument developed by the author for relaying and recording is likely to find useful applications. It seems to me that its most practical and important features depend, first, on the fact that the acceleration (force/mass) is very great and consequently has high speed possibilities; and secondly, that this acceleration is obtained not by reducing the mass but by obtaining a great force, with the result that the action is robust and therefore likely to possess stability. How the instrument will compare in reliability with other apparatus remains to be seen. It is pretty certain that the coefficient of friction, $\mu$, between two surfaces ground to such accuracy of fit as that mentioned in the paper must yield an apparently higher figure than those generally quoted in textbooks. Thus, the coefficient of friction between parts of the Johnsen gauges must be enormous, for they are ground down to such accuracy that molecular forces play a very prominent part. In fact, the normal pressure on the surfaces in some cases amounts to many atmospheres. Under such conditions the normal pressure on the surfaces must vary at an enormously rapid rate with the distance. In the author's apparatus a rough grinding would probably produce a tangential force $F = \mu f A$ with a radial mechanical force $f$ and a $\mu$ of about the ordinary textbook magnitude. Careful grinding, however, brings into play, possibly, a molecular attraction $f_1$, and consequently a new tangential force $\mu(f + f_1)A$, producing an *apparent* rise in the coefficient as defined mechanically. The application of the magnetic force $B^2A/8\pi$ probably raises the value of $f_1$ to, say, $f_2$ by bringing the surfaces into still more intimate contact, thus giving finally a tangential force $\mu(f + f_2 + B^2/8\pi)A$. Moreover, the purely mechanical force $f$ tends to disappear as the evenness and intimacy of the surfaces increase, with the consequence that the action becomes more and more molecular in character. Altogether the action on the shoe is likely to be a complicated one.

**Mr. H. H. Harrison** (*communicated*): The recorder described by the author belongs to the trigger type of relay, in which a comparatively small initial amount of energy controls the liberation of a much greater quantity. A comparatively recent example of this type is furnished by the Johnsen-Rahbek apparatus, depending upon the electrostatic effect between a flexible shoe partially surrounding a rotary drum or roller formed of lithographic stone. The general principle of the shoe-drum type of trigger goes back much further than this and its possibilities are such that I think a brief description of two such arrangements will be of interest. Fig. A represents a form of loudspeaker devised in 1901 by D. Higham. The primary vibratory diaphragm, actuated by means not shown, is mechanically connected to the free end of a horizontal lever HL the opposite end of which is pivoted at a fixed point. Depending from HL is a link L on which a shoe S is hung. S rests on a rotating drum and normally slips freely on this. The shoe is further connected, as shown, to a secondary vibratory diaphragm B. The action is fairly obvious. As A moves to and fro in response to speech currents, it varies the friction between the shoe and the drum and thus the pull of the shoe on the secondary diaphragm. The arrangement of Fig. B (i) is rather more interesting as it sets out to accomplish the precise objects of the author's apparatus, viz. simultaneously to operate a recording siphon and close repeating contacts with an energy far in excess of that originating the operation. D is a drum rotated by means of pulley P through a motor not shown. To the recorder coil RC two cords are attached and from thence they pass to a cradle C, being wrapped two or three times round the rotary drum on their way. The cradle carries a contact arm and also a siphon (not shown). Fig. B (ii) shows a variation, both arrangements being invented by Piedfort in 1895. As the recorder coil shown in Fig. B (ii) oscillates, it alternately tightens and loosens the cords wrapped around the drum, the tightened cord acting as a coil clutch to couple the drum to one or other arm of the cradle, C. This arrangement of Piedfort's works extremely well and can be applied with advantage where both relayed and recorded signals are required. It will give square-shaped signals at high speeds but, unless the relaying feature is required, the complications of this or any equivalent device hardly seem worth while. In the author's apparatus, the short transit time gives nice, square signals regardless of their amplitude. When such signals have to be read for some time, the type of signal giving the least fatigue is one in which the amplitude is not too great nor the paper speed so low as to crowd the signals together. The siphon arrangements are admirable. The idea of gripping the siphon at the inking end is a good

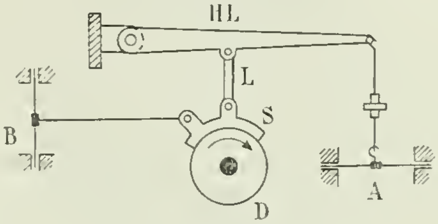


Fig. A.

one, as the trace is free of all oscillations which would otherwise have to be damped out by increasing the paper friction. When the siphon is power-driven, however, the ordinary type of siphon can be employed, substituting stiff brass tubing for the ordinary silver tube. Making the inkpot end of the siphon coincide with its centre of oscillation is good and was first carried out by S. G. Brown (British Patent 3 325/1911). I notice that the lever pressing the paper on to the drawing roller controls the paper-carrying roller by means of a link. This arrangement permits of instantly stopping the paper without interfering with the motor and simultaneously withdrawing the paper from the siphon, and was designed and first applied by Mr. S. R. Smith to the "Undulator" made by the Automatic Telephone Manufacturing Co. The author has successfully demonstrated that the design of a telegraph instrument is not a rule-of-thumb matter, but involves engineering considerations as fully as does the design of any other mechanism.

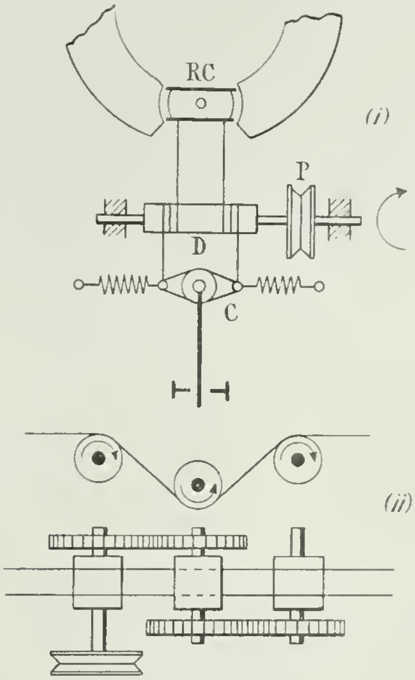


Fig. B.

**Dr. N. W. McLachlan** (*in reply*): Mr. Campbell Swinton's reference to the methods of bygone days requires some qualification. The origination or invention of a method calls, in general, for much less effort than its application to meet the demands of modern practice. The example which he cited of Bell's telephone is a case in point. Whereas the original telephone was merely a qualitative instrument which functioned in a certain way, its development into an instrument of precision the performance of which can be accurately analysed has necessitated a vast amount of work, not only in regard to telephones, but in other directions too. Whereas the original telephone applied to broadcasting would give badly distorted and in some cases unintelligible sounds, the modern instrument is comparatively free from such inherent defects, and their elimination has called for great ingenuity and much technical skill. Prior to Mr. Campbell Swinton's reference, I was unaware of Dolbear's paper, and I can say that, had I been familiar with it, not one moment of the time which has been spent on the development of the present instruments would have been saved.

Mr. Campbell Swinton and Mr. Brown have constructed apparatus similar to that of Dolbear, but evidently with disappointing results. Taking this in conjunction with the scant information in Dolbear's short paper of about 400 words, I am inclined to think that his results were more of an anticipatory than of a real nature (based on the results of Edison's Motograph). I think that Mr. Campbell Swinton's description of the apparatus as a *loud-speaking* telephone is incorrect, for according to his own experiments "there was a good deal of noise, but not *articulation*."

Bearing in mind the status of workshop practice in a university or a college in the year 1879, there is every reason to believe that the surfaces of contact used were very imperfect. No quantitative measurements were made of the magnetic condition of the materials. Had this been done, nothing unusual would have been discovered, since the particular effect on which the action of the present apparatus depends, only occurs to any appreciable extent when the surfaces fit one another extremely well and are free from foreign matter. If the sensitivity had exceeded appreciably that of Bell's telephone, it is highly probable that the device would have been commercialized, but it would have lacked sensitivity unless the rubbing surfaces had been as just stated. It may thus be inferred that the magnetic or magneto-cohesion phenomenon on which the instruments described in the present paper depend for their operation, was not discovered by Dolbear. In fact, its existence can only be determined by accurate measurements on the magnetic condition of the shoe.

The relationship between the drum speed for the key and the pull has been raised by Mr. Ewen. As stated in Section (14) of the paper, the variation is more accidental than real and is of no practical importance, provided the drum is not allowed to become too warm. This cannot occur, owing to the draught from the fan. Mr. Ewen's remark on the advantage possessed by the transmitting key puts the question very clearly and concisely. The requirement is a large force per unit current, and, in virtue of the new phenomenon, this ratio can be made extremely large with moving parts of small mass. In Appendix II I have given data respecting the performance of the new key, and I hope that these will meet Mr. Ewen's requirements.

Dealing with the question of relaying from a valve circuit to a printing machine or other device, Mr. Carpenter states that a well-designed relay will operate on *much* smaller current-changes than the magnetic drum type. This statement is incorrect, and in practice —it is idle to quote laboratory data where signals are perfect, and to which the reference was probably made—the magnetic drum type will function with precision *as a relay and as a recorder* at 100 w.p.m. on 4 mA, whereas the usual type of relay requires (for precision work) a current of from 10 to 15 mA each way, which is approximately equivalent to 20 to 30 mA single current. Thus an ordinary relay performs only one function,* and requires from 5 to 7·5 times the current. As regards bias, the marking and spacing on the magnetic drum type can be varied over a much wider range than is the case with any relay which is in unstable equilibrium when the moving part is in its magnetically symmetrical position, e.g. the Post Office, A.T.M., and Carpenter relays. Furthermore, the magnetic drum type is stable, and the adjustment is never accompanied by a sudden cessation in operation due to holding over on one of the stops.

Concerning square signals, to which objection is raised, it is my own experience, and that of others in this country and in America, that operators undoubtedly prefer such signals, and this is the reason why they are used in practice. The recorder of the Radio Corporation of America, to which reference concerning proportional representation is made, also gives square signals. As it works between stops it does not give proportional representation. Moreover, I fail to grasp Mr. Carpenter's conclusions on proportional representation, especially as his own experience in America appears to have been obtained from this instrument. Perhaps he has mistaken it for the instrument designed by Mr. Hoxie of the General Electric Co., Schenectady. Mr. Hoxie's apparatus is a form of a vibration galvanometer tuned to about 2 000 periods, and, since it is not critically damped and the frequency is low, truly proportional representation is impossible. The cathode ray oscillograph is the only existing type in which truly proportional representation is possible. Moreover, it is necessary to resort to photographic reproduction, and although the signals in some cases *might* be more legible than in others, the method is at present ruled out in commercial work owing to its high cost. Strictly proportional representation has points to recommend it, and, although rough preliminary experiments appear to show that it may have advantages, one is reminded of the multitude of miraculous devices which were invented a few years ago for paralysing parasites, none of which was of much use. In these days when radio telegraphy is being attacked in a scientific manner, the most effective weapon that the wireless engineer can wield against these foes is found to be a simple series of selective circuits.

Coming now to fixed-stop apparatus: with the magnetic drum recorder and an appropriate receiving circuit it is readily possible to discriminate between signals and atmospherics, even when the latter are troublesome. This would not apply, however, to the usual form of electromagnetic recorder. I think that Mr. Carpenter has been confusing the so-called Undulator type recorder with the Morse pattern. The latter is certainly of the "all or nothing" variety, and in this respect I would refer him to my remarks in the discussion on Lieut.-Col. Cusins's paper (see *Journal I.E.E.*, 1922, vol. 60, p. 260). The fixed-stop recorder is as yet by no means ruled out by the Marconi Co. in this country, or by the Radio Corporation in America for transoceanic commercial recording, and is in everyday use on both sides of the Atlantic. The results obtained in practice justify the use of such instruments.

Mr. Carpenter's final remark on the "complexity of the adjustments" is opposed to fact. As stated explicitly in the paper, no adjustment is necessary when the speed of signalling is varied, and there is great latitude in the initial setting of the control spring and of the CR unit. During the demonstration I showed no fewer than eight different experiments illustrating the various physical properties of the instrument. Hence adjustments were necessary.

As Mr. Joseph remarks, no application has yet been attempted in connection with cable telegraphy. Concerning working currents, I would refer him to Appendix I. I think that the best way to deal with cable recording would be to insert a valve circuit between the instrument and the cable, for then the inductance of the former would not interfere with the wave-form of the incoming current. To obtain an adequate working current is merely a matter of cascading suitable valves in an appropriate manner. At the demonstration the current through the recorder was about 2 mA, the circuit of Fig. 11 being employed, details of which are given. I greatly appreciate Mr. Joseph's admiration for the workmanship, and for this I am indebted to those whose names are mentioned at the end of the paper. The drums are always turned in a lathe on their own ball bearings, this being a special and necessary feature of the design. I have always insisted upon extreme accuracy, for this eliminates the possibility of trouble in the future. The precise diameter of the drum is, of course, immaterial.

No trouble has been experienced with the shoe contact on the drum, even at sea.* In this respect it may be of interest to know that the first model is now on the "Majestic," and good results have been obtained at high speed, the recorder being placed direct in the valve circuit. I do not anticipate trouble in humid atmospheres, because there is sufficient heat generated at the surface to prevent hydrous lubrication. Likewise no difficulty has been encountered due to the wear of the shoe.

In reply to Mr. Tilley, the reason for using Swedish iron in preference to steel for the spindle is to enhance demagnetization on cessation of the signal current, so that the siphon lever returns rapidly to the back stop. The surfaces should always be kept free from grease or moisture. Occasionally a clean, dry rag may be used to remove any dust or other matter, but this is really unnecessary. On the recorder very little grinding occurs, and the surfaces become polished. With the keys, where the working forces are larger and the shoe becomes warm, grinding probably occurs to a certain extent, but it cannot well be avoided. The brushes used on the brass slip-rings may be of either morganite or bronzcol, but as these materials were not to hand at the time, ordinary carbon brushes were inserted and the rings smeared lightly with vaseline.

---

* In practice it is usual to keep a check slip of the messages, and therefore a recorder is necessary.

* See *Wireless World*, 1923, vol. 12, p. 124; *Electrician*, 1923, vol. 90, p. 291; and *Wireless Weekly*, 25 April, 1923.

The answers to Mr. Shaughnessy's queries will be found in the paper and in Appendix I. He will see that the desired "infinitesimal current" of 10 $\mu$A at 100 w.p.m. is a practical proposition. Contrary to what Mr. Shaughnessy says, the Gulstad device of "oscillating" is not used in practical work with the magnetic drum instruments; it merely serves as an illustration of one of the properties of the instrument. The experiment to illustrate excessive paper friction has a practical bearing on the problem of relaying from the recorder, since delay in reaching the back stop is detrimental to the record at the far end of the line (see Fig. 22, No. 6).

Mr. Murray's reminiscence of S. G. Brown's experiment brings to my mind a well-known seaport device, viz. the hydraulic capstan. I saw this apparatus some 23 years ago at Silloth, in Cumberland, when several wagons weighing, perhaps, 70 tons were hauled along by a man pulling lightly on one end of a rope wound several times round the capstan head.

In replying to Messrs. Carpenter and Shaughnessy, I have almost covered the points mentioned by Major Binyon. A perusal of the paper and Appendixes I and II ought to convince Major Binyon that a method yielding a higher degree of precision with smaller working currents must be superior to its predecessors. I was not aware that proportional representation on a moving, non-sensitized tape could be accomplished by many well-known methods, and I fear that Major Binyon is under the same impression regarding proportional representation as Mr. Carpenter.

Magnification to any desired degree by a valve is hardly the problem at issue, for the force obtainable with the ordinary pattern of recorder is limited ultimately owing to heating of the coils. Moreover, in this respect alone an instrument giving a much greater force per unit current for a moving system of definite mass is to be preferred. In addition, if the number of valves required can be reduced, this is also beneficial, since it minimizes the possibility of spurious reaction, lessens the working and capital costs and saves space. Incidentally I may mention that the magnification is not purely mechanical, but depends on magnetism as an accessory.

Concerning the Johnsen-Rahbek effect cited by Major Lefroy, I have no experimental experience in this direction, and, so far as I am aware, the effect has not been satisfactorily explained, nor have calculations been performed on the same lines as those in Section 14 of the present paper. I have no data with which to compare the performances of the two instruments, but I can state without hesitation that the magnetic drum instrument is unaffected by the humidity of the atmosphere and climatic conditions in general, and it is much stronger mechanically than any other form of recorder yet constructed. It is primarily a current-operated device, whilst the Johnsen-Rahbek instrument is voltage-operated.

Replying to Mr. Brown, I think that the electrostatic telephone of Dr. Elisha Gray was the pioneer of its type,* and it was due to this instrument that Edison's attention was directed to telephony, his Motograph being evolved as a consequence. From the description given of the revolving drum relay, the force acting on the stylus is apparently equal to the product of the coefficient of friction and the force with which it is pressed on the drum, whereas in the present instrument there is also the additional force resulting from the magnetic effect described in Section 14. Thus the magnetic drum device must be many times more sensitive, especially if sensitivity is defined broadly as "force per unit mass of moving system for a given current." In this respect I would refer Mr. Brown to the curves and data in Section 14, and also to Appendix I, where it is shown that an instrument can be made to function at 100 w.p.m. on a current of 10 $\mu$A.

It does not seem to have been generally realized that, for a given moving mass, much larger forces can be obtained per unit current with the magnetic drum apparatus than with other methods. This is due to (1) the absence of an air-gap in the magnetic circuit through the shoe, and (2) the new phenomenon, which augments the force (as expected by calculation) manifold. The principle of the apparatus is such that the energy input is almost entirely (except for the initial $\frac{1}{2}Li^2$) utilized in causing a pull on the shoe, and could be very small if a considerable reduction in the resistance of the coil were possible, whereas, in an ordinary relay, part of the energy input is converted into kinetic energy of the moving system. In the magnetic drum apparatus the energy is supplied by an external source, and hence the appliance is an energy amplifier.

Mr. Davies sums up in symbolic form what I had in mind when writing Section 14, which describes the sliding force between drum and shoe. It would appear that molecular forces are brought into play, but I agree with Mr. Davies that "the action on the shoe is likely to be a complicated one." The shape of the (experiment/calculation) curve supports the theory of molecular action, since after the surfaces are brought sufficiently near to give the peak on the curve, the ratio falls off, as would be expected, for the degree of closeness will not increase to any considerable extent. Mr. Davies's preliminary remarks are absolutely to the point. As regards reliability, several instruments have been in operation for 18 months without giving any trouble.

In reply to Mr. Harrison, I think that Higham's amplifier is of scientific interest but of no value in practice as a telephonic device, owing to the distortion arising from the method employed. I appreciate the Piedfort relay, because I have made experiments on similar lines. Such instruments require careful handing, however, and are of a delicate nature. The magnetic drum recorder is an instrument which is strong and—to use a vulgarism—"fool-proof." The advantages of the latter quality are too obvious for comment. The record showing Wheatstone working was obtained by slightly tilting the platen over which the paper runs, so that the tape was inked only when the tongue rested on the marking stop. The friction paper drive shown in Fig. 1 has now been superseded, as I find it more satisfactory to drive straight from the worm gear and vary the speed of the motor by means of rheostats. Mr. Harrison's remarks are most encouraging. He has fully grasped the features incorporated in the design, which are so essential for success in commercial service.

---

* Patented in 1875.

---

# THE DESIGN OF INDUCTANCES FOR HIGH-FREQUENCY CIRCUITS.

By Professor C. L. Fortescue, Member.

(*Paper first received* 24*th October*, 1922, *and in final form* 30*th January*, 1923; *read before the* Wireless Section, 2*nd May*, 1923.)

### Summary.

This paper consists of an investigation of the proportions and the arrangement of the winding of high-frequency inductances in order to obtain the minimum ratio of $R/L$. Both stranded and solid wire coils are dealt with, and the unavoidable limitations arising from the space factor are considered. Results and tables are given which enable simple comparisons to be made between stranded and solid wire coils having either single- or multiple-layer windings.

## 1. Introduction.

The necessity of designing inductances with the minimum ratio of resistance to inductance presents itself at both the transmitting and receiving stations in all branches of wireless communication. The relative advantages of stranded and solid conductors and the best form of the coil have been discussed frequently with somewhat indeterminate results. Many sources of power loss are known to exist, but in this paper only the losses in the metallic parts of the conductors are considered, and an attempt has been made to determine, for any given conditions, whether stranded or solid conductors are preferable and what is the best form of the coil so that the metallic losses shall be as small as possible. Numerical examples are given at the end showing that as far as these losses alone are concerned it is possible to design compact coils having a low resistance; and from these figures it follows that the reduction of the dielectric losses is in practice the controlling factor.

The methods adopted are a continuation of previous work, particularly of the unpublished work of Mr. H. A. Madge, carried out in the autumn of 1914 when he was in the Wireless Department of H.M.S. "Vernon," Portsmouth. The author desires to thank the Admiralty for permission to publish the figures of Table 1 of this paper which are derived very largely from Mr. Madge's computations. Important papers on this subject have also been published by Prof. G. W. O. Howe[*] and Mr. S. Butterworth.[†] The latter deals with certain aspects of the problem very rigorously indeed and it is interesting to note that the approximate methods adopted in this paper are in agreement with his results.

## 2. The Losses in a Coil of Finely Stranded Wire.

If properly arranged with respect to one another all the strands will carry their proportionate share of the current, and the power expenditure will be due to:

(i) The conductor losses, assumed in this case to be the same as for steady currents.

(ii) The eddy-current losses in the conductors due to the main field of the inductance.

These two losses may be calculated separately and then added.[*]

Let $d_1$ denote the diameter of the individual strands in cm.
$n$ denote the number of strands laid up into each conductor.
$\lambda$ denote the wave-length in metres.
$\rho$ denote the specific resistance of the conductor in ohms per cm per cm$^2$.

Then for 1 cm length of strand the simple conductor resistance is $1\cdot 27\,\rho/d_1^2$ ohms. For $n$ strands in parallel the resistance per cm will be $1\cdot 27\,\rho/nd_1^2$ ohms. For 1 cm length of strand placed with axis perpendicular to an alternating magnetic flux

$$B_t = \sqrt{2}B \sin \omega t$$

and assuming that the eddy current in the wire is so small that the flux is not materially altered by it, the eddy-current loss is

$$\frac{17\cdot 4\, d_1^4 B^2}{\rho\lambda^2} \text{ watts}$$ [†]

The value of $B$ will vary throughout the coil and the total loss will be found by calculating the average value of $B^2$.

The value of $B$ at any point near the coil is directly proportional to the current carried by the conductor and to the number of turns, but inversely proportional to the linear dimensions for a coil of given form. The average value of $B^2$ may therefore be written

$$Av.\,B^2 = K^2 I^2 N^2 / D^2$$

where $I$ is the R.M.S. current per conductor, $N$ the number of turns, $D$ the overall diameter in cm. and $K$ a constant depending upon the form of the coil.

---

[*] *Proceedings of the Royal Society*, 1917, vol. 93 (A), p. 468.

[†] *Philosophical Transactions*, 1922, vol. 222 (A), p. 57.

[*] G. W. O. Howe: *loc. cit.*

[†] *Ibid.*

Thus the average loss (in watts) per cm length of strand throughout the whole coil is

$$17 \cdot 4\left(\frac{d_1^4}{\rho\lambda^2}\right)\left(\frac{K^2N^2}{D^2}\right)I^2$$

The average contribution of each cm length of strand towards the total resistance of the inductance is thus

$$17 \cdot 4\left(\frac{d_1^4}{\rho\lambda^2}\right)\left(\frac{K^2N^2}{D^2}\right) \text{ ohms}$$

For a conductor made up of $n$ strands the contribution per cm length towards the total resistance will be

$$17 \cdot 4\left(\frac{nd_1^4}{\rho\lambda^2}\right)\left(\frac{K^2N^2}{D^2}\right) \text{ ohms}$$

Thus the total resistance per cm length of the whole stranded conductor is

$$1 \cdot 27\left(\frac{\rho}{nd_1^2}\right) + 17 \cdot 4\left(\frac{nd_1^4}{\rho\lambda^2}\right)\left(\frac{K^2N^2}{D^2}\right) \text{ ohms}$$

Regarding the number of strands in the conductor as the variable, this total resistance is a minimum when

$$n = 0 \cdot 27\left(\frac{\rho\lambda}{d_1^3}\right)\left(\frac{D}{KN}\right) \quad . \quad . \quad . \quad . \quad (1)$$

The total number of individual strands over the whole winding section for the minimum resistance is thus :—

$$nN = 0 \cdot 27\left(\frac{\rho\lambda}{d_1^3}\right)\left(\frac{D}{K}\right) \quad . \quad . \quad . \quad . \quad (2)$$

The minimum resistance per cm length of conductor corresponding to this number of strands is

$$9 \cdot 4\left(\frac{d_1}{\lambda}\right)\left(\frac{KN}{D}\right) \text{ ohms} \quad . \quad . \quad . \quad . \quad (3)$$

### 3. THE RESISTANCE OF A COIL HAVING A SOLID CONDUCTOR.

This is a much more difficult quantity to calculate. As in the case of the stranded conductor the losses will be due to two causes, viz. :—

(i) The conductor losses due to the distribution of the main current over the skin of the conductor.

(ii) The losses due to the surface distribution of eddy currents set up by the main flux, which for large conductors tends towards such a distribution that no flux penetrates the conductor.

These two losses, when calculated, may be added in order to determine the effective resistance of the whole coil.

The conductor resistance may be found from any of the usual formulæ. But for high frequencies and large conductors the distribution over the surface of the conductor is practically the same as the distribution in the case of an infinite flat surface, viz.

$$j = j_0 e^{-mz} \sin(\omega t - mz)$$

$j$ being the current density in amperes per cm$^2$ at a depth $z$ in the material, $j_0$ the current density at the surface, and

$$m = \sqrt{\left(\frac{2\pi\omega}{\rho}10^{-9}\right)}$$

for materials of unit permeability.

The effective resistance per cm length of a strip 1 cm wide of such a surface is

$$\rho m = 3 \cdot 44\sqrt{(\rho/\lambda)} \text{ ohms}$$

Applying this for a large cylindrical conductor of diameter $d_2$ cm, the resistance per cm is

$$\frac{1 \cdot 10}{d_2}\sqrt{\frac{\rho}{\lambda}} \text{ ohms}$$

which is a practical form of what is usually known as Rayleigh's approximation.

In order to determine the losses arising from the currents induced by the main flux, it is necessary to find what surface distribution of current will just prevent the magnetic flux from penetrating the conductor. It is well known that if the current down the outside of a cylinder is distributed over the circumference according to a sinusoidal law, then the flux density within the cylinder is constant (see Appendix 1). Consequently, a sinusoidal distribution of eddy current of the right magnitude will prevent a uniform external flux from penetrating the conductor.

If the current (see Fig. 1) is

$$j' = j'_{max.} \sin\phi$$

where $j'$ is the surface density of the current at angle $\phi$, the uniform field within the cylinder is

$$B' = \left(\frac{2\pi}{10}\right)j'_{max.}$$

Thus, to balance an alternating flux

$$B_t = \sqrt{2}B \sin wt$$

the current necessary is

$$j = j_{max.} \sin wt \sin\phi$$

where $$\left(\frac{2\pi}{10}\right)j_{max.} = \sqrt{2}B$$

The R.M.S. value of the current at the maximum position will be

$$\frac{j_{max.}}{\sqrt{2}} = \frac{10}{2\pi}B$$

In order to determine the resistance losses the depth to which this surface eddy penetrates must be ascertained. Since the conditions are almost identical with the case of the flat conductor it is reasonable to suppose that as a close approximation the variation of the current with the depth of penetration into the conductor will be the same. On this assumption the losses per cm length are

$$13 \cdot 7 d_2\sqrt{(\rho/\lambda)} \, . \, B^2 \text{ watts}$$

and the contribution per cm towards the total resistance is

$$13\cdot7 d_2\sqrt{\left(\frac{\rho}{\lambda}\right)}\cdot\frac{K^2N^2}{D^2}\text{ ohms}$$

Thus the total resistance per cm of conductor in an inductance made up of a large solid conductor is

$$\frac{1\cdot094}{d_2}\sqrt{\left(\frac{\rho}{\lambda}\right)}+13\cdot7 d_2\sqrt{\left(\frac{\rho}{\lambda}\right)}\cdot\frac{K^2N^2}{D^2}\text{ ohms}$$

Regarding $d_2$ as a variable, this resistance is a minimum when

$$d_2 = 0\cdot286\left(\frac{D}{KN}\right) \quad . \quad . \quad . \quad . \quad (4)$$

With this value of $d_2$, the resistance in ohms per cm length of conductor is

$$7\cdot7\frac{KN}{D}\sqrt{\left(\frac{\rho}{\lambda}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

It is interesting to note that so long as the wave-length is small enough for these calculations to be applicable, the best value for $d_2$ is the same for all wave-lengths.

A simple method of ascertaining whether the methods of this paragraph may be safely used is to determine the depth at which the exponential factor $e^{-mz}$ has some low value, e.g. 0·01. If the radius of the conductor is some three or four times this depth then these methods are applicable. If, on the other hand, this depth is something larger than the radius of the conductor it shows that the methods of Section 2 will give better results.

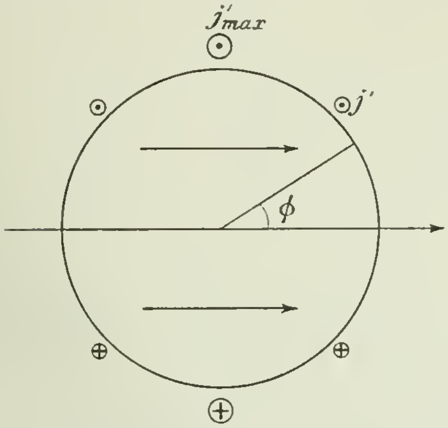


Fig. 1.

Putting $e^{-mz} = 0\cdot01$, $z = 1\cdot34\sqrt{(\lambda\rho)}$

The methods of Section 2 may therefore be used when $d_2$ is equal to or larger than about 10 times $\sqrt{(\lambda\rho)}$.

More elaborate methods of testing the applicability of the formulæ have been given by both Howe and Butterworth.

### 4. THE DETERMINATION OF THE FORM COEFFICIENT, $K$.

This has been calculated by a step-by-step method, the results being given in Table 1.

These values are only given to two places of decimals as the method of calculation (see Appendix 2) is very laborious and the results have not been worked out to a higher degree of accuracy. It should be added that this table has been calculated on the assumption that the current in the conductor is the same throughout the coil. The results will not hold, therefore, with wave-lengths near the natural wave-length of the coil.

### 5. THE INDUCTANCE OF THE COIL.

For a given form, the inductance varies as the square of the number of turns and directly as the linear dimensions, and may be written

$$L = L_0N^2D \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where $L_0$ is a constant which can be calculated to a sufficient degree of accuracy for designing purposes from any of the well-known formulæ.

TABLE 1.

*The Form Coefficient, K.*

$b \equiv$ *Axial length of the coil.*
$t \equiv$ *Winding depth of the coil.*

| $\frac{b}{D} =$ | 0·5 | 0·75 | 1·0 | 1·25 | 1·5 |
|---|---|---|---|---|---|
| $\frac{t}{D} = 0\cdot0$ | 0·99 | 0·68 | 0·52 | 0·43 | 0·37 |
| 0·1 | 0·77 | 0·55 | 0·44 | 0·37 | 0·31 |
| 0·2 | 0·65 | 0·48 | 0·38 | 0·32 | 0·27 |
| 0·3 | 0·57 | 0·42 | 0·33 | 0·28 | 0·24 |
| 0·4 | 0·52 | 0·37 | 0·29 | 0·24 | 0·21 |

Table 2 gives values of $L_0$ for various ratios of the axial length, $b$, and the winding depth, $t$, to the overall diameter, $D$; $L$ being given in microhenrys and $D$ being in cm.

TABLE 2.

*Values of $L_0$.*

| $\frac{b}{D} =$ | 0·5 | 0·75 | 1·0 | 1·25 | 1·5 |
|---|---|---|---|---|---|
| $\frac{t}{D} = 0\cdot0$ | 0·01062 | 0·00824 | 0·00670 | 0·00567 | 0·00496 |
| 0·1 | 0·00774 | 0·00618 | 0·00510 | 0·00435 | 0·00380 |
| 0·2 | 0·00580 | 0·00459 | 0·00380 | 0·00323 | 0·00280 |
| 0·3 | 0·00402 | 0·00325 | 0·00271 | 0·00235 | 0·00204 |
| 0·4 | 0·00264 | 0·00218 | 0·00185 | 0·00160 | 0·00142 |

### 6. THE MINIMUM RATIO OF $R/L$ FOR AN INDUCTANCE.

The length of wire in an inductance of $N$ turns is

$$l = \pi N(D - t) \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Thus, for a stranded wire having the best number of strands, the ratio $R/L$ from (3), (7) and (6) is

$$\frac{29\cdot6}{D}\cdot\frac{d_1}{\lambda}\cdot\frac{K}{L_0}\left(1-\frac{t}{D}\right)\text{ ohms per microhenry}$$

For a large solid conductor, having the best diameter, the ratio $R/L$ from (5), (7) and (6) is

$$\left(\frac{24\cdot3}{D}\right)\sqrt{\left(\frac{\rho}{\lambda}\right)}\cdot\frac{K}{L_0}\left(1-\frac{t}{D}\right) \text{ ohms per microhenry}$$

The factor $\frac{K}{L_0}\left(1-\frac{t}{D}\right)$ appears in both cases and is given in Table 3.

TABLE 3.

*Values of* $\frac{K}{L_0}\left(1-\frac{t}{D}\right)$.

| $\frac{b}{D}=$ | 0·5 | 0·75 | 1·0 | 1·25 | 1·5 |
|---|---|---|---|---|---|
| $\frac{t}{D}=0\cdot0$ | 93 | 82 | 78 | 76 | 75 |
| 0·1 | 90 | 80 | 78 | 76 | 73 |
| 0·2 | 90 | 83 | 80 | 79 | 77 |
| 0·3 | 99 | 90 | 85 | 83 | 82 |
| 0·4 | 118 | 102 | 94 | 90 | 89 |

These values point towards long coils of small winding depth, but the change is remarkably small over a considerable range.

### 7. THE SPACE FACTOR.

With stranded conductors the area of cross-section of copper divided by the whole area of the winding space, for the number of strands corresponding to the minimum resistance, is

$$nN\frac{\pi d_1^2}{4}\Big/bt$$

which, from (2), becomes

$$\frac{0\cdot21}{D}\cdot\frac{\rho\lambda}{d_1}\cdot\frac{1}{K}\Big/\left(\frac{b}{d}\cdot\frac{t}{d}\right) \quad . \quad . \quad . \quad . \quad (8)$$

For a solid conductor of diameter giving the minimum resistance, this ratio is $N\frac{1}{4}\pi d_2^2/bt$, which from (4) becomes

$$0\cdot064\frac{1}{NK^2}\Big/\left(\frac{b}{D}\cdot\frac{t}{D}\right) \quad . \quad . \quad . \quad . \quad (9)$$

In the case of single-layer coils of solid conductor a more important ratio is the fraction of the whole winding length occupied by the conductor, namely $Nd_2/b$, which from (4) becomes

$$\frac{0\cdot29}{K}\Big/\frac{b}{D} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

### 8. THE LIMITATIONS ARISING FROM THE SPACE FACTOR IN TRANSMITTING INDUCTANCES.

i. *Stranded conductor.*—With multiple-layer stranded coils used for transmitting purposes the spacing of the conductors necessary to avoid sparking between turns or losses in the intervening insulating material makes it very difficult to realize a space factor exceeding **0·2.** That is, from (8)

$$\frac{0\cdot21}{D}\cdot\frac{\rho\lambda}{d_1}\cdot\frac{1}{K}\Big/\left(\frac{b}{D}\cdot\frac{t}{D}\right) \not> \text{about } 0\cdot2$$

whence

$$\frac{\lambda}{D}\not>\frac{Kd_1}{\rho}\cdot\frac{b}{D}\cdot\frac{t}{D}$$

Assuming copper conductors, for which $\rho=1\cdot8\times10^{-6}$, this becomes

$$\frac{\lambda}{D}\not>5\cdot6\times10^5 d_1K\frac{b}{D}\cdot\frac{t}{D}$$

Table 4 gives the maximum values of $\lambda/D$ when $d_1 = 0\cdot01524$ cm (No. 38 S.W.G.).

TABLE 4.

*Maximum values of $\lambda/D$ ($\lambda$ in metres, $D$ in cm) for a Stranded-conductor Coil having a Space Factor not exceeding 0·2 and for a Diameter of Strand of 0·01524 cm.*

| $\frac{b}{D}=$ | 0·5 | 0·75 | 1·0 | 1·25 | 1·5 |
|---|---|---|---|---|---|
| $\frac{t}{D}=0\cdot01$ | 41 | 43 | 43 | 44 | 46 |
| 0·05 | 190 | 200 | 200 | 210 | 220 |
| 0·10 | 330 | 350 | 370 | 400 | 400 |
| 0·20 | 550 | 620 | 640 | 690 | 690 |
| 0·30 | 730 | 810 | 840 | 900 | 930 |
| 0·40 | 890 | 960 | 990 | 1 020 | 1 070 |

The maximum values of $\lambda/D$ in Table 4 can be used for any other diameter of strand or any other space factor by simple proportion. For example, if $d = 0\cdot0457$ cm (No. 26 S.W.G.), all the values in the table will be multiplied by 3.

ii. *Solid conductor.*—Allowing the same space factor for multiple-layer transmitting coils wound with solid conductor, expression (9) must not exceed 0·2, i.e.

$$0\cdot064\frac{1}{NK^2}\Big/\left(\frac{b}{D}\cdot\frac{t}{D}\right)\not>0\cdot2$$

whence, by substituting $N=\sqrt{(L/L_0D)}$

$$\frac{L}{D}\not<0\cdot1\frac{L_0}{K^4}\Big/\left(\frac{b}{D}\cdot\frac{t}{D}\right)^2$$

It is only with very shallow coils that this limitation is felt in practice. Table 5 gives minimum values of $L/D$ for $t/D = 0\cdot01$ and $0\cdot05$.

In many cases single-layer solid-conductor coils are employed, and, allowing a minimum spacing between the conductors of one-half their diameter, expression (10) must not exceed 0·67, i.e.

$$K\frac{b}{D}\not<0\cdot43$$

TABLE 5.

*Minimum Values of $L/D$ ($L$ in microhenrys, $D$ in cm) for Solid-conductor Multiple-layer Coils, the Space Factor not exceeding* $0\cdot2$.

| $\frac{b}{D} =$ | 0·5 | 0·75 | 1·0 | 1·25 | 1·5 |
|---|---|---|---|---|---|
| $\frac{t}{D} = 0\cdot01$ | 45 | 68 | 98 | 116 | 130 |
| $0\cdot05$ | 2·5 | 3·7 | 4·5 | 5·0 | 5·9 |

Table 6 gives the values of $K\frac{b}{D}$ for the low values of $t/D$, from which it will be seen that no difficulties arise from this condition in single-layer coils.

TABLE 6.

*Values of* $K\frac{b}{D}$.

| $\frac{b}{D} =$ | 0·5 | 0·75 | 1·0 | 1·25 | 1·75 |
|---|---|---|---|---|---|
| $\frac{t}{D} = 0\cdot0$ | 0·50 | 0·51 | 0·52 | 0·54 | 0·55 |
| $0\cdot1$ | 0·39 | 0·41 | 0·44 | 0·46 | 0·47 |

### 9. THE LIMITATIONS ARISING FROM THE SPACE FACTOR IN RECEIVING INDUCTANCES.

Although it is not necessary to provide for considerable sparking distances between turns in these inductances, it is generally found that a space factor higher than $0\cdot2$ cannot be realized unless the conductors are wound tightly together, a construction leading inevitably to large dielectric losses. If any form of air spacing is adopted, the same difficulties are experienced as with the transmitting coils, very often in an accentuated form owing to the fact that the volume of the coil is limited and less efficient coils have to be accepted.

### 10. THE RESISTANCE OF COILS IN WHICH THE CONDITIONS FOR MAXIMUM EFFICIENCY CANNOT BE COMPLIED WITH.

Limitations arising from the space factor or from other considerations often enforce a departure from the ideal conditions, and it becomes a matter of importance to determine the effect of this departure on the resistance of the coils.

If $y = ax + (b/x)$, $y$ has a minimum value when $x = \sqrt{(b/a)}$, given by $y_{min.} = 2\sqrt{(a/b)}$. For any other value of $x$, say $x'$, the corresponding value of $y$, viz. $y'$, is given by

$$y' = ax' + \frac{b}{x'} = y_{min.}\,\tfrac{1}{2}\left(\frac{x'}{x} + \frac{x}{x'}\right)$$

Applying this result to a stranded-wire coil, if the number of strands is $n'$ instead of that given by (1) the resistances all through will be multiplied by a factor

$$\tfrac{1}{2}\left(\frac{n'}{n} + \frac{n}{n'}\right)$$

In the case of the solid-wire coil, if the diameter of the conductor is $d_2'$ instead of the value given by (4), all the resistances will be multiplied by the factor

$$\tfrac{1}{2}\left(\frac{d_2'}{d_2} + \frac{d_2}{d_2'}\right)$$

If the departure from the ideal conditions is not great, these factors differ but little from unity. But for large departures the factors gradually approach one-half the ratio of the larger to the smaller.

### 11. GENERAL CONCLUSIONS.

With either stranded or solid conductors the minimum value of $R/L$ varies inversely with the diameter of the coil. Since the value of $\frac{K}{L_0}\left(1 - \frac{t}{D}\right)$ varies comparatively little over the region $b/D = 1\cdot0$ to $1\cdot5$ and $t/D = 0\cdot0$ to $0\cdot2$, it follows that there is considerable choice for the shape of the coil. In most practical cases the tendency will obviously be to make $b$ as little greater than $D$ as possible. If $b = D$ there is little choice between a single- or multiple-layer coil, so long as the desired number of strands or diameters of solid conductor can be provided for.

Taking a round figure of 80 for $\frac{K}{L_0}\left(1 - \frac{t}{D}\right)$, the ratio $R/L$, in ohms per microhenry, becomes $\frac{2\,400}{D} \cdot \frac{d_1}{\lambda}$ and $\frac{2\,000}{D}\sqrt{\frac{\rho}{\lambda}}$ respectively, for the stranded and solid conductors.

The first of these varies as $\lambda^{-1}$ and the second as $\lambda^{-\frac{1}{2}}$. Thus, for any given values of $d_1$ and $\rho$ there is a particular wave-length for which these ratios are equal, and for that wave the stranded and solid conductors give equally efficient coils.

For shorter waves the solid conductor is preferable, and for longer waves, the stranded one ; *always assuming that the space available is sufficient for the strands required and for the best diameter of solid conductor.*

Assuming that cost of manufacture imposes a limit of $d$, $\nless 0\cdot01524$ cm (i.e. No. 38 S.W.G.) for the strands of a stranded conductor for small coils, and putting $\rho = 1\cdot8 \times 10^{-6}$ for copper, the wave-length for which stranded and solid conductors are equally effective is 186 m. For a diameter of strand of $0\cdot0457$ (i.e. No. 26 S.W.G.) the wave-length at which the coils are equally effective is 1 670 m.

It may be observed that these conclusions do not depend upon the accuracy with which the form coefficient $K$ is computed.

### 12. Numerical Examples.

(i) A transmitting inductance of 1 200 $\mu$H, diameter 500 cm, $b = D$ and $t = 0{\cdot}1\,D$, $\lambda = 8\,000$ m, number of turns $= 21{\cdot}7$.

(*a*) Stranded copper conductor,

$d_1 = 0{\cdot}0457$ cm (No. 26 S.W.G.), $\rho = 1{\cdot}8 \times 10^{-6}$

Strands in conductor = 2 140.
Resistance of coil = 0·032 ohm.

(*b*) Stranded aluminium conductor,

$d_1 = 0{\cdot}1625$ cm (No. 16 S.W.G.), $\rho = 3{\cdot}0 \times 10^{-6}$

Strands in conductor = 79.
Resistance of coil = 0·11 ohm.

(*c*) Solid (or tubular) copper conductor, $\rho = 1{\cdot}8 \times 10^{-6}$
Diameter of conductor = 15 cm.
Resistance of coil = 0·068 ohm.

In these cases no limitations are experienced from the space factor.

(ii) A receiving inductance of 10 000 $\mu$H, as compact as possible, such that the resistance does not exceed 20 ohms for a wave-length of 8 000 m.—Stranded copper conductor, $d_1 = 0{\cdot}01523$ cm, $\rho = 1{\cdot}8 \times 10^{-6}$.

Preliminary trials show that the space factor is all-important in this case. Allowing a space factor of 0·2 the maximum value of $\lambda/D$ from Table 4 will be about 1 000 for $(b/D) = 1{\cdot}0$ and $(t/D) = 0{\cdot}4$.

This gives: $D = 8{\cdot}0$ cm, 823 turns, about 38 strands per conductor, and a resistance of about 6·6 ohms. These figures show that a smaller diameter could be used with less than the ideal number of strands. For example, $D = 5{\cdot}0$, $(b/D) = 1{\cdot}0$, $(t/D) = 0{\cdot}4$, requires 1 040 turns and an ideal number of strands of 18. Putting 9 strands only gives a resistance of about 13·5 ohms with a space factor of 0·18.

It is interesting to notice that the comparatively high-resistance coil of small dimensions tends to become a coil of deep section. The present-day tendency of certain manufacturers of apparatus for the use of amateurs is thus fully justified from the point of view of the copper losses. The construction of these coils becomes almost entirely a problem of providing a suitable insulation between turns and layers. It is also interesting to note that a single-layer coil of the same diameter and inductance as the above would have a resistance of over 600 ohms.

## APPENDIX 1.

The following proof of the relationship in question has been suggested to me by Prof. C. Godfrey, Royal Naval College, Greenwich.

Let P (Fig. 2) be a point within the conductor and let two chords intersecting at P at a small angle $d\alpha$ cut off elements of the circumference $ds$ and $ds'$ at Q and Q′ respectively.

Let OT be the perpendicular bisector of the mean chord, and let the angle BOT be denoted by $\alpha$. Then the angle $d\alpha$ between the chords is the change of the angle $\alpha$ from one chord to the other.

Let the equal angles TQ′Q, TOQ, TOQ′ and TQQ′ be denoted by $\psi$, then $\angle \text{QOB} = \alpha - \psi$ and $\angle \text{Q'OB} = \alpha + \psi$

Assuming the sine distribution of current

$$j' = j'_{max.} \sin \phi \text{ (see Fig. 1)}$$

the current in the element $ds$ is

$$j'_{max.} \sin (\alpha - \psi) \,.\, ds$$

and the current in $ds'$ is

$$j'_{max.} \sin (\alpha - \psi) \,.\, ds'$$

Now $\dfrac{\text{PQ}d\alpha}{ds} = \sin \psi$; i.e. $ds = \dfrac{\text{PQ}d\alpha}{\sin \psi}$

and similarly $\qquad ds' = \dfrac{\text{PQ'}d\alpha}{\sin \psi}$

The contribution of the currents in the two elements $ds$ and $ds'$ towards the flux density at P in the direction TO is

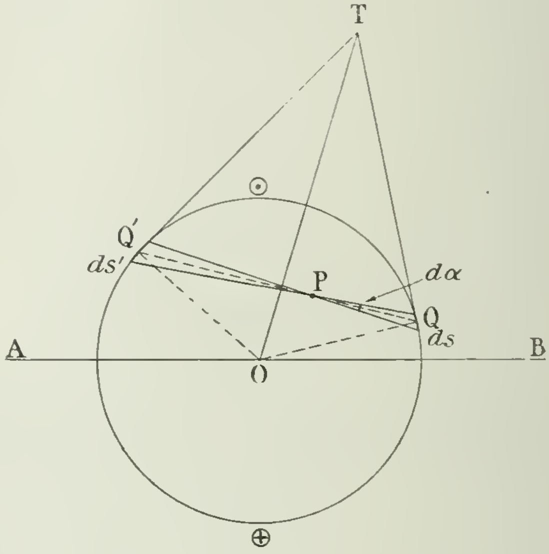


Fig. 2.

$$\frac{2}{10} j'_{max.} \left\{ \frac{\sin (\alpha - \psi)}{\text{PQ}} \cdot \frac{\text{PQ}d\alpha}{\sin \psi} - \frac{\sin (\alpha + \psi)}{\text{PQ}'} \cdot \frac{\text{PQ}'d\alpha}{\sin \psi} \right\}$$

$$= -\frac{4}{10} j'_{max.} \cos \alpha \,.\, d\alpha$$

The component of this field vertically upwards is

$$\frac{4}{10} j'_{max.} \cos \alpha \,.\, \sin \alpha \,.\, d\alpha$$

and the horizontal component in the direction AB is

$$\frac{4}{10} j'_{max.} \cos^2 \alpha \,.\, d\alpha$$

Integrating each of these terms from $\alpha = 0$ to $\alpha = 2\pi$ each element of current is included twice. Hence the vertical component at P

$$= \frac{2}{10} j'_{max.} \int_0^{2\pi} \cos \alpha \sin \alpha \,.\, d\alpha = 0$$

and the horizontal component in the direction AB

$$= \frac{2}{10} j'_{max.} \int_0^{2\pi} \cos^2 \alpha \,.\, d\alpha = \frac{2\pi}{10} j'_{max.}$$

## APPENDIX 2.

The method adopted to calculate the form coefficient was as follows:—

The winding section of the coil was divided into a number of sections A, B, C, etc. (Fig. 3). Then, for each section in turn, the contribution towards the field strength at the centre point of that section from the current in *each* of the other sections was calculated in the form of vertical and horizontal components. The vertical and horizontal components respectively were added and the mean square of the field strength was found. This was done for each section of the coil and an average was taken.

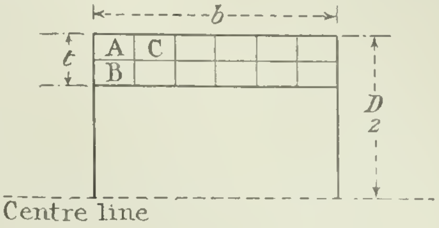


Fig. 3.

The accuracy of the results depends upon the number of subdivisions of the winding section. For determining the values of $K$ given in Table 1 only a small number of subdivisions were taken. For a larger number the calculations become very laborious.

This method is undoubtedly clumsy, but, so far as the author is aware, no other is available.

## Discussion before the Wireless Section, 2 May, 1923.

**Mr. S. Butterworth:** The author has dealt with a difficult problem, using very simple methods. These simple methods are only possible by making suitable approximations. Thus the diameter of the wire is assumed to be either so small that the losses vary as the square of the frequency, or so large that the losses vary as the square root of the frequency. As the author points out, the limiting diameter for either of these laws is determined by the value of $\sqrt{(\lambda\rho)}/d$. As regards the thinnest wire for which the "square root" law is applicable, the formula for the resistance per cm of an inductance made up of a large solid conductor is more accurately given by

$$(1 \cdot 1/d) \sqrt{(\rho/\lambda)}\,[1 + 0 \cdot 3 \sqrt{(\lambda\rho)}/d] + 13 \cdot 7 d \sqrt{(\rho/\lambda)}\,[1 - 0 \cdot 3 \sqrt{(\lambda\rho)}/d] K^2 N^2/D^2$$

when $\sqrt{(\lambda\rho)}/d$ is less than $0 \cdot 82$. The author's simplified formula will therefore hold to 3 per cent for both skin losses and proximity losses if $\sqrt{(\lambda\rho/d)}$ is less than $0 \cdot 10$. If, in accordance with the author's recommendations, the skin losses are made equal to the proximity losses [see Equation (4), Section 3] it is seen from the above formula that the "square root" law will hold for much thinner wire, so that we may take as the limiting diameter for this law $d = 1 \cdot 2 \sqrt{(\lambda\rho)}$. As regards the "square" law, if $d = 0 \cdot 83 \sqrt{(\lambda\rho)}$ the skin losses are about 8 per cent higher, and the proximity losses about 6 per cent lower, than those given by the simple theory. There is thus again a cancelling effect which pushes up the limit of application of the "square" law to $d = 0 \cdot 83 \sqrt{(\lambda\rho)}$ in the case of "ideal" coils. The author has deduced that stranded wire coils and solid wire coils give the same resistance when $d \doteqdot 0 \cdot 8 \sqrt{(\lambda\rho)}$, which is just about the limit of application of the square law for stranded wire. Since the resistance rises more slowly at shorter wave-lengths, the statement that stranded wire coils are inferior to solid wire coils above the frequency specified has hardly been proved. I have shown in the paper referred to by the author that stranded wire coils may always be constructed which are better than solid wire coils containing the same amount of copper, provided proper precautions are taken in regard to spacing. The choice is really a question of expense and mechanical construction at the shorter wave-lengths. Another important approximation has also been made. It has been assumed that the field over the section of the conductor is uniform. This limits the distance of the wires. The non-uniformity of the field when the wires are close together has only been studied in two cases, viz. a coil of two turns and an infinitely long solenoid. The former case may be treated by a method due to Mr. F. J. W. Whipple, and the result in the case of touching wires at very high frequencies is that the ordinary skin resistance must be multiplied by 4/3. The uniform-field theory gives for this factor 3/2. In the case of the long solenoid the exact theory gives $3 \cdot 41$ and the uniform-field theory $5 \cdot 94$. Thus the uniform-field theory overestimates the losses when the wires are close together. This is rather important as it affects the rule for the ideal diameter. In fact, I find that if the diameter of the wire is varied in the case of the long solenoid, the minimum eddy-current resistance is obtained with the wires touching. The "form coefficient" $K$ given in Table 1 depends not only on the form but also on the number of turns, the number of layers, and on whether the wire is stranded or solid. Thus for single-layer solenoid coils having a large number of turns, I have obtained the following values of $K$ by fairly rigorous methods:—

| $b/d$ | 0·5 | 0·75 | 1·0 |
|---|---|---|---|
| $K$ | 0·83 | 0·58 | 0·46 for solid wire |
| $K$ | 1·00 | 0·69 | 0·84 for stranded wire |

The author gives the following values of $K$: 0·99, 0·68 and 0·52. For very short coils the value of $K$ is infinite but $Kb/d$ is finite. In this case, if we put $U_n = (5Kb/D)^2$ we have the following values for short single-layer coils :—

| Turns .. | 2 | 4 | 8 | 16 | 32 | infinite |
|---|---|---|---|---|---|---|
| $U_n$ .. | 1·00 | 1·80 | 2·37 | 2·74 | 3·00 | 3·29(= $\frac{1}{3}\pi^2$) |

For $m$-layered coils with a large number of turns per layer, $U_n = \frac{1}{3}\pi^2(2 - 1/m^2)$. Finally, I cannot agree with the author's recommendation that long coils are necessarily the best. In arriving at this result he has assumed the diameter of the coil to be fixed. If, on the contrary, we keep the *volume* of the coil constant, all the numbers in Table 6 must be multiplied by $(b/D)^{1/3}$ and then we obtain the least time-constants when the coils are short. In fact, if we take coils the length of which is equal to the radius instead of the diameter, we find that the resulting design for coils of given inductance and resistance demands less copper and no greater overall space is required. I have elsewhere recommended coils the length of which is equal to one-third their diameter and for which the spacing is such that the proximity losses are one-third the skin losses. The considerations leading to these conclusions were that the diameter and length of wire were given, and with this design the value of $R/L$ was a minimum. It should be noted that the minima concerned are usually very flat and, therefore, where current considerations are of no importance it is often desirable to reduce the diameter from the "ideal" diameter, as this results in a considerable economy in copper, with very little increase in resistance.

**Mr. T. L. Eckersley:** The author has put the subject of high-frequency eddy-current losses in coils in a very clear manner, and although in many cases measured results do not agree with the calculated values this does not in the least detract from the value of the paper, for it is absolutely essential to know what results should follow from the simple assumptions made therein before the case of faulty coils can be clearly diagnosed. In connection with the measured values of inductances, which at wireless frequencies are almost invariably measured by a resonance circuit, there always exists some doubt in one's mind, as the author has said, as to whether the resistance actually measured is the resistance of the coil. If the condenser is not perfect the measured resistance includes the effective resistance of the condenser as well as that of the coil. It is of great importance, therefore, to try to devise a method by which the resistance of the coil alone or of the condenser alone can be measured. Some time ago I devised the following method. A perfect condenser should be a pure reactance; the current through it and the voltage across it should be in quadrature. The only other thing which is a pure reactance is a mutual inductance. It should be possible, therefore, to balance the one against the other, and this can be done by Campbell's bridge method. If the condenser is perfect a balance can be obtained, but if there is any loss in the condenser, which can be represented by a series resistance, no balance can be obtained. By a slight modification of the arrangement as shown in Fig. A the resistance in the condenser can be ascertained. The arrangement adopted is to shunt the primary of the inductance $L_1$ with a resistance $R_1$ and condenser $C_1$ in series. If we assume that the resistance of the inductance $L_1$ is negligible the current flowing in the shunt winding $R_1C_1$ is practically 180° out of phase with the current flowing through the condenser C. On tracing out the circuits it will be found that the resistance-drop down the resistance $R_1$ is in the opposite sense to that down R and by suitably adjusting $R_1$ the two can be balanced. The condition for balance is approximately $R = (R_1 p^2 L_1 C_1)/(1 - p^2 L_1 C_1)$. I have actually used this method in measuring an air condenser of the order of 0·07 $\mu$F, which was previously considered to be nearly perfect. By an arrangement of this sort we found that its resistance was 0·15 ohm, which was a large proportion of the total resistance of the coil we were trying to measure. This shows how misleading it may be to try to measure the resistance of a coil if the resistance of the condenser is not accurately known. The method which I have described could, of course, be used to measure the resistance of the coil. On performing this test we found that the resistance of the coil was actually smaller than that of the condenser. In this method it is absolutely essential to have a perfectly shielded oscillator to supply the energy to the circuit and to couple with a mutual inductance in which there is practically no electrostatic induction. We found our signal-measuring apparatus to be specially suitable for this work.

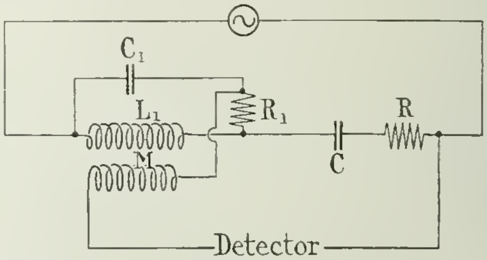


Fig. A.

**Mr. F. C. Lunnon:** The paper is particularly interesting to us, because for a long time we have been trying to make transmitting coils of a resistance which will not swamp the resistance of a good aerial. Our aim has been to make a coil with a resistance of less than 0·1 ohm per 1 000 $\mu$H. We have succeeded in doing this, but not with commercial stranded wire. Attempts to do it with commercial stranded wire have invariably failed, the actual value always being very much in excess of the calculated value. In the case of one transmitting coil of 1 300 $\mu$H, in which the conductor consisted of over 2 000 strands of No. 36 wire, the high-frequency resistance (calculated) at a wave-length of 15 000 m should have been only 5 per cent greater than the d.c. resistance; actually it was 350 per cent greater. The probable reason for this discrepancy is imperfections in the stranding, and also, as Mr. Butterworth has pointed out, the closeness of the strands one to another. The author does not seem to have touched on this question of the closeness of the strands, but this can be an important factor in the sort of case presented by a transmitting coil, where the turns per unit length, and therefore the main field intensity, are usually small. For example, we have found that in a coil in which the conductor consisted of 8 strands of No. 20 S.W.G. wire, with a winding pitch of 6 cm, the increase in resistance was appreciable when the distance between strands was reduced to less than 0·8 cm, in which case it can be shown that the current in one strand produces a field at its neighbour of the same order of strength as the main field of the coil. With regard to the worked-out example given at the beginning of Section 12 of the paper, apart from the doubt as to whether this very low resistance of 0·032 ohm at 8 000 m could be obtained with commercial stranded wire, there is another reason which also makes it doubtful, namely—and this applies particularly in the case of a coil of so large a diameter as 5 m—the losses in the walls, floor and roof. I do not refer to the elusive dielectric losses, which the author has purposely left out of consideration in the paper, but to losses due to eddy currents induced in the surroundings, which experience has shown can be considerable. For example, in the case of a coil of about half the diameter of the one given in the example, at a height of 6 ft. above the ground the eddy-current loss in the ground was 0·06 ohm at 8 000 m and would of course be greater than this for a coil of greater diameter. In raising these points I am not presuming to cast any doubt on the valuable theoretical conclusions arrived at by the author, but merely to illustrate the practical difficulties of constructing a coil which will actually have a resistance equal to its calculated resistance. The paper deals only with the two extreme cases of finely stranded wire and a solid conductor, but we hope that in the near future the author will investigate the intermediate case of a moderate number of strands of a medium-sized wire.

**Mr. F. E. Nancarrow:** Mr. Lunnon has said that he finds the results obtained in practice from high-frequency resistance measurements to be not in accord with the values derived from utilizing the formulæ given in the paper. I am especially interested in this as I have recently spent much time in taking measurements of the high-frequency resistance of coils as used in practice, and the results, I am afraid, lie in curves much above those which the formulæ given in this paper, or the well-known papers of Professor Howe and Mr. Butterworth, would give rise to. As examples of practical results, curve 1 in Fig. B shows the variation of resistance with frequency of a large stranded-wire coil, whilst curve 2 is for a large copper-tube coil. These curves illustrate the high ratios of high-frequency to d.c. resistance which are met with in practice. The author remarks on the difficulty of taking such measurements: the above measurements were all carried out by the method described in the March number of the *Journal of the Post Office Electrical Engineers* and it is thought that the results, which were readily obtained, are substantially accurate. The surroundings and supports play a large part in the resistance of large coils, and examples are given in the above mentioned paper. Curve 1 in Fig. C gives the resistance value of a small copper-strip coil, whilst curve 2 illustrates the case of a small stranded-wire coil, and here again the values are much higher than those deduced from formulæ. In the case of these coils the curves are three-functioned, consisting of a rapid rise at the low frequencies, then a period of much slower rise of resistance with frequency, followed by another period of rapidly rising resistance with increasing frequency. Measurements taken on model coils both with copper strip and stranded wire give results which exhibit this three-fold characteristic to a greater or less degree, and it is interesting to note that Professor Moorcroft in the *Journal of the Institute of Radio Engineers* for August 1922 shows curves of resistance for very much smaller coils than those considered here, taken at much higher frequencies than those I have given, which exhibit similar characteristics. I should be glad if the author could advance any information to account for this particular shape of resistance curve. In the measurements taken on the model coils where the effect of surroundings was reduced to a minimum, all the results were much higher than those derivable from the papers previously quoted.

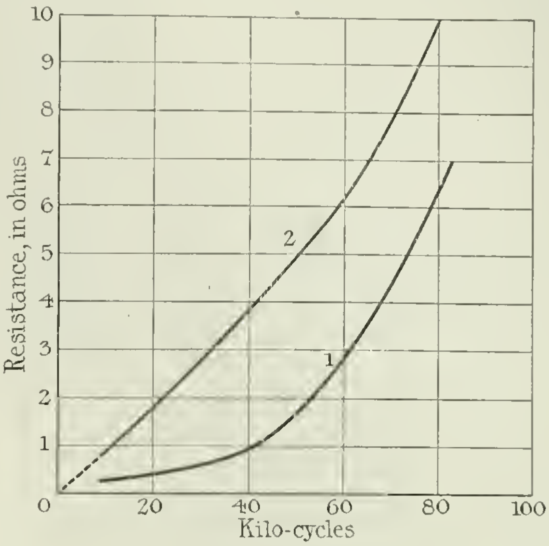


Fig. B.

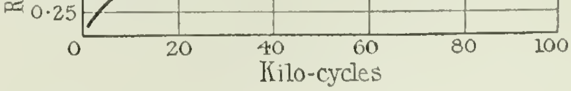


Fig. C.

**Mr. R. V. Hansford :** I cannot help having a little grievance against the mathematicians of our profession. My grievance is that these eminent scientists entice engineers to struggle through long detailed mathematical arguments by titles such as "The design of inductances," in which the mathematics, although extremely clever and interesting, does not account for all the factors and in consequence is of little practical application. I have had occasion recently to make some design calculations, and I have been surprised to find how the calculated resistances according to the formulæ of the author, Prof. Howe and Mr. Butterworth agree between themselves in giving results so different from the actual measured values. This seems to apply especially to the case of transmitting inductances for medium-power and high-power stations where the frequency is only moderately high. In a case I have in mind, which is typical, the calculated ratio of high-frequency resistance to d.c. resistance varied from 1·03 to 1·09 according to the formula used, whereas the actual measured ratio was 2·0. This discrepancy was probably due to losses in the coil supports and in the surroundings, but clearly it does not seem of much use to obtain the optimum value with respect to the dimensions of an inductance very carefully from the point of view of reducing the losses in the metal itself by an amount which is a very small proportion of the total, when there is no certainty that the proportions of the coil are correct in respect to the other losses, which are many times greater. This is especially the case when, as the author points out, the ratio of length to diameter of coil is not of very great importance, and is emphasized by the fact that apparently the mathematicians themselves are far from being in perfect agreement ; whereas the author suggests a ratio of length to diameter of about 1, Mr. Butterworth states in his paper before the Royal Society that the optimum ratio is 0·31.

**Professor G. W. O. Howe :** I think that Mr. Hansford's grievance is somewhat misdirected ; it should not be against the mathematicians, as he calls them. The mathematicians give formulæ for ideal coils, and I think that his grievance should be directed against the manufacturers, who are not making ideal coils. When I was working on this subject I encountered the problem of what the author calls the "form coefficient," which necessitates the calculation of the flux at various points throughout coils of various shapes, and at various times I nearly made up my mind to tackle it, but the procedure required was so laborious that I always postponed it. The result is that my formulæ for coils were always based on infinitely long coils, and a very rough approximation was applied to shorter coils. When I first tackled this problem, some years ago, multiple-strand wire was used on every possible occasion. My calculations led me to the conclusion that in many cases it would have been far better to use solid wire. My results were so contrary, not only to the general belief but to my own conceptions, that I at first doubted their accuracy. The general impression was that it was especially necessary to use multiple-strand wire if the frequency was very high, but I found that was just the case where solid wire should be used. The author brings out that point in his "General Conclusions," where he states : "For shorter waves the solid conductor is preferable, and for longer waves, the stranded one." That is what I found ; but it was so contrary to the generally accepted belief at that time that people were, as a rule, inclined to disbelieve it. Another result I obtained which also surprised me was that with a multiple-strand wire of given overall diameter it was not the best policy to pack as many little wires as possible into it ; the resistance could be decreased by pulling out some of the wires and decreasing the space factor, because by so doing the eddy-current losses were reduced and the steady current losses increased in the same proportion, so that the total high-frequency resistance was reduced so long as the former exceeded the latter. I did not, however, bring my results into such a practical form for general application to the design of coils, as the author has done, and I am sure that the paper will constitute a very useful addition to the literature on the subject and be of great assistance to the designers of coils, for, as Mr. Eckersley has pointed out, even though one does not obtain a formula which takes into account all the practical imperfections of an actual coil, one must, in the first place, have the ideal calculation to know what to expect under ideal circumstances before one can introduce corrections and modifications to take account of the secondary losses which occur.

**Professor C. L. Fortescue** (*in reply*) : Mr. Butterworth has dealt at length with the corrections which are necessitated by the approximate methods adopted in the paper. His conclusions are in close agreement with the statements made in the paper, and the corrections which he points out are a valuable addition to it. He criticizes the conclusions with regard to the limiting wave-length at which stranded conductors are advantageous. There is no doubt that this wave-length is by no means sharply defined and it is not suggested that this is the case. The fact remains, however, that the critical wave-length determined by the methods given in the paper is a good practical guide. Also, it is not in dispute that stranding will always lead to a lower resistance than the use of solid conductors if it is practicable to use the very fine strands which become necessary with short waves. But for practical purposes these fine strands are ruled out and the solid conductor then becomes preferable. The assumption of a uniform field is certainly not justified for the coils of a very few turns mentioned by Mr. Butterworth, but for the considerable number of turns generally employed the errors are in most cases within 1 or 2 per cent. With regard to the best shape of the coil, the whole point of Table 3 of the paper is to call attention to the fact that the shape can be varied over a wide range without appreciably altering the ratio $R/L$. The corresponding figures worked out in terms of the volume are as given in Table A. This table accentuates still more the fact that the shape has little effect.

Mr. Butterworth's final remark is very true, and Section 10 of the paper was especially inserted to deal with cases of this kind.

Mr. Eckersley quotes some measurements of the resistance of an air condenser which bring out the great difficulty of measuring the low resistances of some large inductances. The fact that he has obtained reliable results at wireless frequencies with the bridge described is very interesting.

Table A.

*Values of* $\frac{K}{L_0}\left(1-\frac{t}{D}\right)\sqrt[3]{\frac{b}{D}}$

| | $b/D$ | 0·5 | 0·75 | 1·0 | 1·25 | 1·5 |
|---|---|---|---|---|---|---|
| $\frac{t}{D}$ | 0·0 | 74 | 75 | 78 | 82 | 86 |
| | 0·1 | 72 | 73 | 78 | 82 | 84 |
| | 0·2 | 72 | 76 | 80 | 85 | 88 |
| | 0·3 | 79 | 82 | 85 | 89 | 94 |
| | 0·4 | 94 | 93 | 94 | 97 | 104 |

The results quoted by Mr. Lunnon suggest faulty construction and, failing more detailed information, no explanation can be given. Numerous measurements made by the author have shown discrepancies of this kind and the causes, e.g. broken strands, bad insulation between turns, etc., have always been found. The losses in the surrounding walls and floors can be easily overcome by suitable screening. The intermediate case, fortunately, only arises to any great extent in the case of stranded wire coils for short waves. The difficulty can usually be overcome by plotting curves of the extreme cases and smoothing them off so that they run into one another. The result is necessarily very approximate, but short of very elaborate calculations it is the only one known to the author.

Mr. Nancarrow's curves are interesting and point to some other source of loss, presumably dielectric loss between the turns.

With regard to Professor Howe's early experiences, the explanation is now sufficiently obvious. It does not matter what form of inductance is used; if stranded conductor is employed there will be a certain number of strands which will give the best result for a given wave-length.

# DISCUSSION ON

## "PERMISSIBLE CURRENT LOADING OF BRITISH STANDARD IMPREGNATED PAPER-INSULATED ELECTRIC CABLES." *

**Messrs. S. W. Melsom** and **E. Fawssett** (*in reply*): The many favourable comments that have been made as to the value of the report are greatly appreciated by all concerned. Some of the points raised in the discussion, more particularly those dealing with the recommendations of the Research Association, have been specifically considered by the Association, and we may deal with these first.

(1) *Maximum permissible temperature.*—The Association has given careful consideration to the criticisms made at every meeting at which the report has been discussed, with regard to the recommended maximum permissible temperature of 50° C. for plain lead-sheathed cables drawn into ducts. It will be noted that the experiences of some of the speakers at the Birmingham meeting bear out the view that serious trouble may be experienced due to the movement of the cable in the duct, and the Association desires to adhere to its previous recommendation.

In addition to the question of abrasion of the lead sheathing, there is the probability that in a duct line where accumulation of hot air may occur at one place, the temperature may be higher than the value of 50° C., which, it should be noted, is the average conductor temperature.

In the case of the armoured cables drawn into ducts mentioned by Mr. Ratcliff, it is clear that the question of abrasion does not enter, and for such cases the Association recommends a maximum permissible temperature of 60° C., i.e. a temperature-rise of 45 degrees C. The Association recommends, however, that precautions should be taken to anchor the end of the armouring to prevent the cable slipping along the duct. The simplest way of arriving at the requisite value of this temperature-rise is to multiply the figures given for armoured cables in air in Tables 16 to 21 inclusive, by a factor of 1·05, which multiplication will give nearly the correct current for the same cables drawn into ducts, for a rise of 45 degrees C.

(2) *Differentiation in the value of the thermal resistivity of the dielectric, $K$.*—The different values of thermal resistivity for the two types of cables are based on experimental determinations, and reference to Table 21 (page 535) shows that while the lower pressure cables gave values ranging from 670 to 1 200, the values for the higher pressure cables were lower and more uniform for different cables, the average of the values being nearly that of the recommended figure of 550. The opinion of the Association was, and still is, that the values recommended are reasonable, and that a further increase should be allowed for the very small cables. This opinion is based on a knowledge of the difference in the manufacturing processes employed; no doubt if the same processes were generally used for the lower pressure as for the higher pressure cables, the values found would be more nearly the same. For lower pressure cables, however, it is often necessary to provide for other and special requirements, which might have the result of increasing the value of $K$, and again the question of cost of manufacture affects the matter. Therefore for the purpose of the report and tables it was necessary to adopt a value based on data obtained experimentally with a number of low-pressure cables of ordinary manufacture.

*Value of the thermal resistivity of the soil, $g$.*—Mr. Townley's suggestion for obtaining an average value of the soil for a particular district, both with regard to moisture content and thermal resistivity, is an excellent one for existing networks or for the extension of the same. In the case of new and important cable lines, however, where different types of soil may be encountered, it is clearly necessary to survey the route from this point of view, and either base the rating on the value of the soil having the highest thermal resistivity, or else increase locally the sectional area of the conductors.

In reply to the other technical points raised:

With regard to Mr. Atkinson's remarks, it is pleasing to note that the report may result in economies of such magnitude. Apart from this, however, the friendly attitude of the cable makers to the research has been most helpful, and the assistance and advice given by individuals on the technical staffs of the various cable works, invaluable.

In connection with Dr. Russell's suggestion that the emissivity constant varies inversely as the square root of the diameter of the cable, we have looked up a large number of results obtained at the N.P.L. and elsewhere on all sorts of materials of widely different shapes and sizes, together with some results of carefully made experiments which will shortly be submitted for publication in another connection. These results show that the inverse-square law does not apply over the whole range of sizes, although it is approximately true for the portion of the curve covering a certain range of size of cylinder. This, however, is much below the range of normal cable sizes; for sizes comparable with those of cables used in practice, say from 0·05 sq. in. upwards, the emission for unit area is practically independent of the size. This is justified by all the observations available, and more particularly by those made by Mr. Watson (see Appendix VI). If the observations given in Tables 61, 62 and 63, page 571, for four different cable sizes are plotted, the slope of the logarithmic curve is very small and fully justifies the adoption of an average value for the emissivity constant.

We fully agree with Dr. Russell that the difference between the results of tests of an actual three-core cable with only two cores loaded and those obtained with the electrostatic model requires further explanation. The figures in the load tables are based on the experiments with the cable, and therefore are to be preferred. With regard to the interesting question as to the existence of a temperature coefficient of the thermal resistivity of the dielectric, examination of a large number of values on different cables, each cable being tested at various temperatures, gives no definite indication of such a temperature coefficient, although it is possible that there may be one.

---

* Paper by Messrs. S. W. Melsom and E. Fawssett (see page 517).

Mr. Rosen gives some interesting data obtained from experiments which would seem to bear out Dr. Russell's suggestion. These data, however, are not in accordance with our own results. The differences found by Mr. Rosen and ascribed to temperature coefficient are very large indeed, and we are unable to understand how, if they are so large, they were not noticed. In any case, however, the suggestion that a temperature coefficient is responsible for the apparent anomalies in the results for the three-core cable with only two cores loaded is not valid, since a complete heating curve was obtained under both conditions, and comparison was made between the currents required for a given temperature-rise.

Mr. Brazil raises the question of the limiting temperature and refers to the higher figures in use abroad and possibly in this country. The point of his remark as to the application of the data given in the report is, however, not quite clear. The value of 65° C. taken for purpose of the calculation of the load tables is not fundamental, but represents the considered opinion of practical men. If, however, any particular inquirer, with full knowledge of his own system, wishes to work at a different figure, the data given will enable him to calculate without much difficulty either the current for any given temperature-rise or the temperature-rise for a given current. Mr. Brazil will appreciate the fact that, in view of the large differences of thermal resistivity occurring with different types of soil of varying moisture content, it is impossible to provide a single figure that will apply to every set of conditions. It should not, however, be difficult to devise comparatively simple tests that would provide the data required for the special case.

In reply to Prof. Marchant, there is no suggestion that the passage of current through a cable tends to increase the moisture content in the immediate neighbourhood. We have to thank Prof. Marchant for drawing attention to the Hele-Shaw method and to the coefficient of expansion of aluminium.

With regard to the point raised as to the incidence of dielectric losses, a large amount of data has been published but a great deal is very conflicting. Some experimenters suggest that the temperature-loss curve falls with increasing temperature with a minimum at about 50° C., and then increases, while others state that the curve is linear for suitably designed cables. In view of this we should prefer not to express an opinion until our own work is complete. The question of sheath losses in single-core cables has not been dealt with in the report.

In reply to Mr. Riley, the calculation of the case of three-core cables used on a three-wire circuit was undertaken at the request of engineers who stated that it was common practice to use three-conductor cable, with all the conductors of the same size, for this class of service. The statement that the balanced-load condition is the least favourable on the score of temperature-rise is quite correct for this case, but obviously it does not necessarily apply to all possible conditions of loading with a cable having a smaller neutral core. The hypothetical case mentioned by Mr. Riley where the out-of-balance current exceeds $\frac{2}{3}I$, is correctly stated. In such a case, however, we should have thought that the type of cable indicated was wholly unsuitable for the condition of loading. We have to thank Mr. Riley for his abstract of Emanueli's work, and for his suggestion of an alternative method of using thermo-couples with a very large model. With regard to the divergences between the British and German tables, the difference in the thickness of the dielectric is not sufficient to account for the difference in the current-loading tables.

Mr. Dunsheath raises the question of the reliability of the method used to make the experimental values fit those calculated by means of the formula. It is agreed that it would have been preferable if a complete formula based on assumptions that were absolutely correct could have been evolved, but possibly the criticism has not taken account of the extremely difficult and complicated nature of the problem as to the lines of heat-flow and the thermal properties of the soil. Under the circumstances, the convenient method of using a formula with appropriate correction purely as an empirical formula for interpolation between points determined experimentally is sound practice and is to be preferred to the use of a formula without experimental proof. Actually this portion of the problem was submitted to eminent mathematicians, who advised that it was best dealt with in this manner. The paragraph on page 541 referred to by Mr. Dunsheath is correct as it stands: it really deals with the difference in current loading between the limit now recommended of 65° C. and the higher limit of 80° C., which is more nearly the value allowed in American practice.

Mr. Hunter asks for further information regarding cables spaced at distances other than those mentioned in the report. The method employed allows the mutual effect of any number of cables at any distance apart to be readily calculated. For the conditions mentioned by Mr. Hunter the current reduction would be as follows:—

Two cables in the horizontal plane:

| Distance apart in. | Ratio of current reduction |
|---|---|
| 18 | 0·91 |
| 24 | 0·93 |

We fully agree with Mr. Hunter that some investigation is required of the special conditions obtained in connection with cables run on racks alongside a railway track. The questions raised involve not only the temperature-rise but also any possible modification of the maximum permissible temperature for the different method of laying. Mr. Hunter rightly draws attention to the number of variable factors, and we hope that it will be possible to act on his suggestion for a special series of tests.

Mr. Rosling kindly draws attention to two or three small points on which correction is necessary, and this has now been done.

In reply to Mr. Williams, quite a fair section of the report (pages 553 to 561) is devoted to intermittent and emergency loading, and a further paper * published since the discussion gives full information as to cables in air or on ships.

---

* *Journal I.E.E.*, 1923, vol. 61, p. 363.

We are pleased to have the contribution from Mr. Del Mar, especially as a sign of the interest taken in the report by American engineers. In reply to the points raised, we fully accept Mr. Del Mar's statement as to the basis of the American values. A somewhat similar point has been raised by Mr. Torchio in correspondence. At the same time the note on page 541 was intended to be a fair, short abstract of a number of papers published in America, which papers all referred mainly to mechanical tests, and perhaps the complete basis was not made quite clear.

The value of limiting temperature is largely a matter of opinion based on experience of operation. Obviously the number of breakdowns per mile per annum, both as regards the cost of repairs and the effect on the public supply, affects the question very largely, and here we would refer Mr. Del Mar to Mr. Dunsheath's remarks on page 582. It would appear that Mr. Del Mar should define more closely the words "operating successfully." Mr. Del Mar objects to the manner in which the question is summarized. Here there is an obvious difference of opinion as to what constitutes logical expression. In the report all the factors are set out in logical sequence, and then comes the statement that the Committee, after consideration of them all, decided to adopt a given value. It is agreed that the selected value is based very largely on opinion, i.e. the same basis as that on which the American values were adopted. We agree that a large amount of work is required to determine the safe working temperatures for dielectrics, and we acknowledge the great assistance afforded by perusal of the American papers to which Mr. Del Mar refers. At the same time, however, it appeared to the Committee that there were several factors, other than those dealt with in the American papers, of which account should be taken, and it is certain that a complete investigation of the subject will occupy a considerable time. Mr. Del Mar suggests that this work has already been done in America, whereas recent programmes of research show that the question is still regarded as unsolved, and important researches dealing with this particular aspect of the question are now being instituted in America. It should be pointed out that the ambient temperature allowed in the report is that of the earth and not that of the air in the duct: previous work has shown the impossibility of using the duct temperature as a basis. This statement affects the figures given by Mr. Del Mar on page 585. We agree that there is some confusion of thought as to Kelvin's law: it is not suggested anywhere in the report that 50° C. is the economical temperature. This must depend on other factors, such as the first cost of cables, deterioration as affected by working temperature, and generating cost. The upper limit is, however, the temperature at which there is appreciable deterioration of the dielectric, with which must be included the number of breakdowns and the cost not only of repairing them but the cost to industry as a result of a temporary failure. In this respect it is quite possible that British and American practice and opinion will differ.

In reply to Mr. Allan, the Research Association did go to a great deal of trouble to obtain as full information as possible regarding Indian and Colonial soil conditions. Moreover, it is moderately easy for the engineers dealing with a projected cable line to obtain the requisite information for any particular locality. Since the printing of the report, however, further information has come to hand from Mr. E. P. Grove regarding the moisture content of the soil in Melbourne, Australia, and this is given in the table opposite.

It will be noted that the moisture content is of the same order as that prevalent in this country, and it is hoped that these figures will help to dispel the opinion held that a hot climate necessarily means a low moisture content of the soil.

The tables of the values in air are based on an ambient temperature of 15° C., with a maximum of 50° C. These are not necessarily standard for air conditions, but the values for any other ambient or final temperature can be readily calculated by means of the formulæ. Thus for an ambient temperature of 30° C., a temperature-rise of 35 degrees C. and final temperature of 65° C., the values of current loading will be approximately 3 per cent less than those given in the tables.

With regard to the question of the error in the term $G$, the reason for this appears to be mainly due to the assumption that the surface of the ground is a plane isothermal.

Mr. Hutchinson's proposed method of obtaining empirical formulæ is interesting. We cannot agree with his comments as to the limitation of the experiments, but would welcome the production of an independent empirical formula.

In reply to Mr. French, the value, $g = 50$, quoted as a good average by some Continental writers is based largely on Teichmüller's work and, as will be seen from the report, is obtained by halving the determined value of 100. The method suggested for obtaining more reliable values of the thermal resistivity of the soil was fully considered, and was felt to be without value for this particular purpose. It must be remembered that the methods used by the Geophysical Laboratories refer to very large depths, whereas in cable practice the total range is in the first 3 ft. or so of the soil. The method is doubtless satisfactory for a great depth, but the portion of the soil near the surface is greatly influenced by atmospheric conditions, rainfall, etc. The effect of these transients will be far greater than that which it is desired to measure, and consequently the method is not applicable. Various soil authorities were consulted on this matter before the decision mentioned above was arrived at.

Some of Mr. Townley's remarks have already been dealt with. In answer to the question as to armouring, the cables used were all of standard type, the armouring being laid on a bedding of jute and served overall with hessian or other tape, and compounded.

Mr. Longman raises a number of interesting points with most of which, and particularly that regarding the method of interspersing lightly loaded with heavily loaded cables, we must agree. In reply to the questions asked: (1) So far as we know, the latest V.D.E. tables are the same as those published in 1905; (2) a considerable amount of work has been done on cables laid on the solid system, and more particularly that of Prof. Marchant published in the previous report. The calculation of load tables was, however, deferred owing to the difficulty of obtaining a reliable value of thermal resistivity of the filling material. The values obtained by Prof. Marchant and at the N.P.L. were nearly 500, but Mr. Beaver in the discussion stated that a value of 300 was more nearly correct. Further investigation showed that various mixtures were in use as filling materials, the thermal resistivity of which varied from 200 to 500, and the extent of this variation and lack of present knowledge of the reason for it has delayed the preparation of the tables. The question of the cables in air along railway cuttings is dealt with in the reply to Mr. Hunter.

| Consecutive No. | Sample No. | Nature of soil | Nature of surface | State of surface | Date taken | Rainfall previous | | Location of trench | Depth taken | | Moisture | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | day | 10 days | | | | | |
| | | | | | | in. | in. | | ft. | in. | per cent | |
| 1 | 1 | Gravelly loam | Grass | Damp | 22/8/21 | — | 0·31 | Dandenong-rd., Caulfield | 2 | 0 | 13·65 | Contained lumps of soft stone, which were powdered and mixed with sample |
| 2 | 2 | Red marl | Grass | Damp | 22/8/21 | — | 0·31 | Dandenong-rd., Caulfield | 4 | 0 | 18·28 | — |
| 3 | 1 | Sandy loam | Grass | Dry | 23/9/21 | 0·42 | 1·66 | Normanby-rd., Caulfield | 2 | 0 | 17·6 | In unmade footpath alongside railway embankment |
| 4 | 2 | Sandy loam | Grass | Dry | 23/9/21 | 0·42 | 1·66 | Normanby-rd., Caulfield | 4 | 0 | 23·8 | Ditto |
| 5 | 1 | River silt (clayey nature) | Grass | Dry | 12/7/21 | 0·2 | 0·22 | Port Melbourne, side of R. Yarra at Spotswood | 2 | 0 | 8·7 | Reclaimed river flats |
| 6 | 2 | River silt (clayey nature) | Grass | Dry | 12/7/21 | 0·2 | 0·22 | Port Melbourne, side of R. Yarra at Spotswood | 4 | 0 | 14·5 | Ditto |
| 7 | 1 | Sandy soil | Grass | Dry | 26/4/21 | 0·01 | 0·72 | Broadway, Camberwell | 2 | 0 | 18·0 | In footpath which was partly asphalt and partly gravel. Trench in gravelled portion |
| 8 | 2 | Red marl | Grass | Dry | 26/4/21 | 0·01 | 0·72 | Broadway, Camberwell | 4 | 0 | 15·3 | Ditto |
| 9 | 1 | Rock and sandstone reef | Asphalt | Dry | 26/11/21 | 0·09 | 1·13 | Bridge-rd., Richmond | 2 | 0 | 7·2 | Shopping centre; trench under verandahs |
| 10 | 2 | Rock and sandstone reef | Asphalt | Dry | 26/11/21 | 0·09 | 1·13 | Bridge-rd., Richmond | 3 | 3 | 5·1 | Ditto |
| 11 | 1 | Yellow clay | Macadam | Wet | 25/11/21 | — | 1·01 | Canterbury-st., Newmarket | 2 | 0 | 25·4 | Trench in water. Table of roadway with 5 in. of metal on pure yellow clay |
| 12 | 2 | Yellow clay | Macadam | Wet | 25/11/21 | — | 1·04 | Canterbury-st., Newmarket | 4 | 0 | 18·2 | Ditto |
| 13 | 1 | Yellow clay | Broken asphalt | Wet | 17/1/22 | 0·01 | 1·0 | Ascot Vale-rd., Ascot Vale | 2 | 0 | 22·7 | Trench in asphalt footpath very much broken up |
| 14 | 2 | Yellow clay | Broken asphalt | Wet | 17/1/22 | 0·01 | 1·0 | Ascot Vale-rd., Ascot Vale | 3 | 0 | 15·5 | Ditto |
| 15 | 1 | Sandy loam on yellow clay | Earth | Dry | 10/2/22 | — | 0·09 | Napier-st., Essendon | 2 | 0 | 9·8 | In unmade footpath. About 1 ft. loam, remainder yellow clay |
| 16 | 2 | Sandy loam on yellow clay | Earth | Dry | 10/2/22 | — | 0·09 | Napier-st., Essendon | 3 | 0 | 12·3 | Ditto |

NOTE.—Cables laid at depths of 3 ft. 0 in. in footpaths, and 4 ft. 0 in. in roadways, the measurement being to the bottom of the cable.

Consecutive Nos. 1, 2, 3 and 4 .. .. .. .. .. .. Jolimont–Caulfield.
Consecutive Nos. 5 and 6 .. .. .. .. .. .. .. Power House, Jolimont (via Fisherman's Bend).
Consecutive Nos. 7, 8, 9 and 10 .. .. .. .. .. .. Jolimont–East, Camberwell.
Consecutive Nos. 11, 12, 13, 14, 15 and 16.. .. .. .. .. Newmarket–Glenroy.

Mr. Woodhouse rightly draws attention to the fact that it will not be economical to run the lower pressure cables at the current-loadings given in the tables. His suggestions for dealing with portions of a cable which may be hotter than the rest are most ingenious, and it will be interesting to see whether they are used in practice.

In reply to Mr. Skinner, the two curves for the years 1911 and 1921 give the highest figures for soil temperature for many years past. With regard to the merging of the tables, the engineers mainly concerned considered that the difference of the order of 5 per cent warranted the preparation of two sets of figures. If more convenient, however, one table only may be used.

The figures of moisture content given by Mr. Bramwell represent valuable additional information, and it is hoped that supply engineers in other districts will have similar observations made.

In reply to Mr. Ratcliff, the general lay-out of the experimental work of a research of this kind is, of course, always open to criticism, since it is impossible to do everything at once, and a single omission leaves room for comment. We would, however, point out that the greater part of the work already done applies to super-pressure cables as well as to the others, and it was both desirable and necessary that the work should include cables of all pressures, since complete verification of the formulæ and constants could only be based on the whole series. The fact that the dielectric-loss portion has not yet been completed, and that in consequence this section cannot be published, does not appear to be a good reason why such a very large number of results should have been withheld. We cannot agree with Mr. Ratcliff's statement as to the method of arriving at the results; these results are all finally based on direct experiment supported by investigation of the separate factors. With regard to the maximum permissible temperature, it is clearly stated in the report that the value of 65° C. for cables buried direct in the ground is a safe maximum for continuous loading conditions, taking into account such factors as the very long life required for such cables and the cost of repair and renewal. If any further information is required with respect to the factors of safety, we would refer Mr. Ratcliff to the remarks of Mr. Del Mar, who assails the figures on the ground that they are too low, and to our comments thereon. The difference between the order of the 2 200-volt and 3 300-volt cables when in air and buried direct in the ground is due mainly to two reasons: (1) that the emissivity constant is not operating when the cable is laid in the ground, and (2) that the tables for 2 200-volt cables apply to a depth of laying of 1 ft. 6 in. and those for 3 300-volt cables at 3 ft. The point as to the thermal resistivity of made ground interspersed with pipes has been dealt with in the reply to Mr. Brazil.

With regard to the very large multi-way ducts, it seems probable that the only method of obtaining evidence of the conditions prevailing is to make actual tests with the ducts. The Committee have had this question fully in mind, but unfortunately the arrangement of multi-way ducts in practice is often such that tests cannot readily be made.

It should be clear that the comparison with a.c. and d.c. tests of three-core cables refers to sizes up to 0·25 sq. in. (each conductor); above this size or at high frequencies there will be additional losses and consequent heating due to such factors as skin effect. We are, however, unable to confirm Mr. Ratcliff's figure of 5 per cent additional losses on account of eddy currents in the lead sheath; even with very large cables the loss should be less than 5 per cent.

Mr. Medlyn's contribution is most interesting, but we are unable to express an opinion as to the reason for the movement of large telephone cables and consequent fracture of the joint.

In reply to Mr. Mallinson, a considerable amount of work has been done with cables laid on the solid system, but it has not yet been possible to produce load tables, on account of the wide divergencies in the value of the thermal resistivity of the bitumen filling material. Tests were made on cables of at least six different makes.

In reply to Mr. Lakeman, there is every reason for a difference between the temperature-rise allowed for cables in air and for those laid direct in the ground. In the latter case it is shown that the base temperature is more generally 15° C. or lower, while in the case of cables in air the ambient temperature may be considerably higher. The values for air are, however, not put forward as standard, but anyone desiring to ascertain the loading for any other temperature will find in the report all the necessary information on which to base his figures.

We cannot altogether agree with Mr. Porter as to the difference between types of ducts. Our experimental data tend to show that the greater part of the thermal resistance is in air in the duct, and consequently the material of the duct will have comparatively little effect.

Mr. Taylor's question as to the relative rating of a 660-volt and an 11 000-volt cable is best explained by the application of the formula to the two cases. In the evaluation which depends on the division of a constant by $\sqrt{(A + S)}$, in the 660-volt cable $A = 99 \cdot 6$ and $S = 34 \cdot 5$, while in the 11 000-volt cable $A = 62 \cdot 3$ and $S = 60 \cdot 5$. Hence the value of $\sqrt{(A + S)}$ in the first case is 11·6 and in the second case 11·1, i.e. the increase in the term due to extra thickness of insulation is more than compensated for by the diminution of the term $A$, which expresses the resistance to heat emission into the air.

With regard to the question of a discrepancy between the new values for a six-core cable and those given in the previous report, the proper value per core was 142. The values given in Table 39 of the present report relate to a temperature-rise of 50 degrees C. and in addition a correction is made for the value of $K$ in the light of the further knowledge on the subject.

With regard to the question as to triple-concentric cables, assuming that the cable has cores of equal cross-section it is probable that the loading could be increased if the innermost core was not carrying any current. The construction of such a cable would, however, be quite different from that of the ordinary triple-concentric, since in the latter case the outer belt of insulation is thinner than the inner. It is, therefore, impossible to give a figure without full knowledge of the dimensions of the special cable, but the formulæ given enable such cases to be worked out.

The interesting accounts of the practical experiences of Mr. Blades and Mr. Groves show that the mechanical troubles considered by the Committee are very real, but these two speakers have shown that with proper design these troubles can be largely avoided.

### ERRATA IN THE PAPER.

It is much regretted that certain errors have crept into some of the equations.

*Equation* 18 should be:

$$S_1 = \frac{K}{6\pi} \log_e \left[ \frac{(0 \cdot 58D + 2 \cdot 15r + E)^3}{r(2r + D)^2} \right]$$

*Equation* 49, line 2 et seq. should read:

"in which $\alpha = \left\{\frac{a + r}{r_4}\right\}^n$ and $\beta = \frac{(a - nr)}{a + nr} \times \left\{\frac{a + r}{r_4}\right\}^n$

The second formula is deduced from (49) upon the . . ."

*Equation* 50 should be: $W = \frac{K}{2\pi L} \log_e \frac{r_4}{r_1}$

*Equation* 51 should be: $r_1 = (a + r) \sqrt[n]{\frac{nr}{a + nr}}$

*Equation* 52 should be:

$$4\pi\,(\text{Capacity}) = \frac{\lambda K}{\text{Thermal resistance}}$$

*Equation* 56, line 2, for $\alpha = \frac{(a + r^3)}{r_4}$ read $\alpha = \left\{\frac{a + r}{r_4}\right\}^3$

*Table* 55. More accurate values for the columns headed $q_M$ would be as follows:—

| Case | $q_M$ | Error of $q_M$ |
|---|---|---|
| 1 | 3·571 | + 6·4 per cent |
| 2 | 3·798 | + 9·6 per cent |
| 3 | 3·345 | + 12·4 per cent |

*Equation* 62 should be: $\frac{\text{Arc CA}}{\text{Arc BA}} = \theta = \frac{r}{r - 0 \cdot 477D}$

*Fig.* 41. $r_3$ should be $r$.

# THE X-RAY EXAMINATION OF MATERIALS.

By A. G. Warren, M.Sc., Member.

[From the Research Department, Woolwich.]

(Lecture *delivered before* The Institution *12th April, before the* Mersey and North Wales (Liverpool) Centre *19th March, and before the* North-Eastern Centre *9th April,* 1923.)

## Introduction.

It will be my endeavour this evening to describe some aspects of radiography as seen from my own particular viewpoint. I shall try to show how the technique of the subject has been developed, and to indicate the lines along which progress may be expected.

Although the theory of radiation is far from complete, the salient elementary facts are fairly generally known and I do not feel called upon to deal with them in any detail. Sir William Bragg covered much of the ground in a lecture delivered before the Institution in 1921.*

Nor need I deal at any length with the applications of X-rays. These are fairly well known and have recently been treated quite fully by various writers. Roughly one can consider the applications as being for medical work, for metal and similar examinations, and for crystallography. Of medical work I shall say nothing; of crystal examination much might be said. It has acquired an entirely new meaning in view of Bragg's researches; an enormous amount of work has already been done and this particular application of X-rays is providing us with a tool of great possibilities. In general this work does not demand a hard or penetrating radiation but one which is as nearly monochromatic as possible. I shall indicate later how such radiations are obtained.

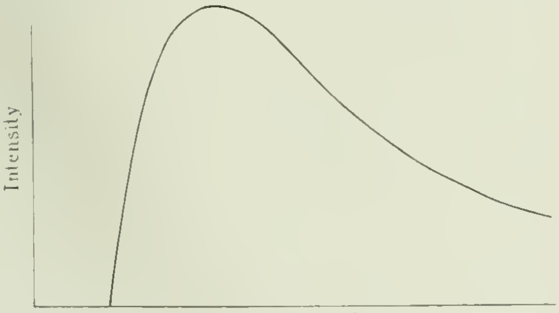


Fig. 1.—Underlying continuous spectrum emitted by a target under electronic bombardment.

The ordinary inspection of metals resolves itself into the detection of faults, e.g. lack of homogeneity, flaws, cavities, presence of foreign materials, bad welds, etc.; the detection of hidden bad workmanship; the examination of sealed bodies which it is undesirable or unsafe to dismantle, such as the examination of shells and fuses to check correct assembly, or the examination of shells of unknown construction; the examination of alloys, etc.

Such work demands quite commonly the hardest radiations that we can obtain, and the application of the method is limited only by the construction of tubes and all the subsidiary gear to withstand and to produce the required pressures. That limit is rapidly being raised, and greater and greater penetrations are becoming possible.

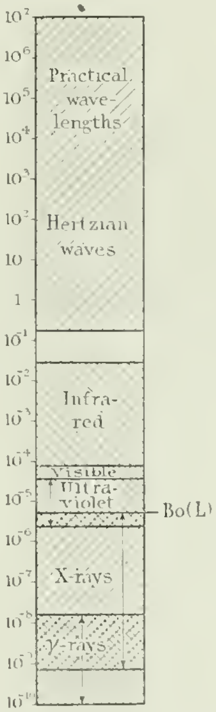


Fig. 2.—Diagram showing lengths in cm of various types of electromagnetic waves. Logarithmic scale.

Radiation is the form in which electrons emit, absorb or exchange energy. It appears to be governed by Planck's hypothesis; that is to say, it exists only in indivisible quanta whose magnitudes are determined by their frequencies. X-radiation is distinguished by the relative greatness of the quanta involved and is produced in the X-ray tube by the rapid deceleration of electrons of considerable energy. An electron hurled against the target is brought to comparative rest in a succession of atomic impacts, giving out an X-ray at each. Much of the radiation produced suffers continuous degradation in the body of the target, but a certain small amount escapes and is represented roughly in distribution as shown in Fig. 1. The short wave-length limit is defined by Planck's equation $h\nu = Ee$, or in practical units $\lambda_{min.} = 12\,400/E$ Ångstrom units (Å.U.). It is seen that the hardness (or frequency) of the radiation is defined by the voltage, $E$. For the voltages we are using, the wave-lengths are very short—about 0·06 to 12 Å.U., or of frequencies some thousands of times as great as those of ordinary light (see Fig. 2).

---

* See *Journal I.E.E.*, 1921, vol. 59, p. 132.

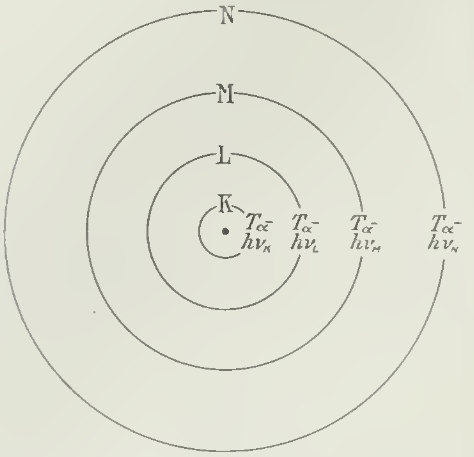


FIG. 3.—Diagrammatic representation of atom, showing energies associated with various orbits or states. ("Fine structure" neglected.)

The process is, in a certain sense, reversible An X-ray of frequency $\nu$ and of quantum $h\nu$ will eject an electron from an outer ring of an atom with an energy equal to $h\nu$ or $Ee$. It would, however, appear that a ray is an indivisible unit which may, or may not, be handed over to an electron; no partial absorption is possible. On the other hand, an electron may be brought to rest in a number of steps. The expected degradation of energy only takes place, therefore, when radiation is emitted; it does not take place when radiation is absorbed. In the procession of radiant phenomena X-rays and moving electrons succeed each other alternately; if we consider more than individual exchanges it hardly seems to matter whether the initial bundle of energy is represented by an X-ray or by an electron. In fact de Broglie makes no distinction but simply talks of the *quantum*, which, although it is an amount of energy, may be described accurately by a frequency, a velocity or a voltage. Regarded from de Broglie's point of view, the pressure of radiation is identical with the mechanical pressure of impinging electrons. Reduced to practical terms this means that when electrons or radiation, or both, encounter matter the result is the emission of an equal amount of energy comprised of radiation proper and of corpuscular radiation, the nature of which depends only upon the matter concerned and the impinging quanta. The radiation is, in the case of X-rays (though not always so for rays of longer wave-length), reduced in frequency or hardness by the encounter.

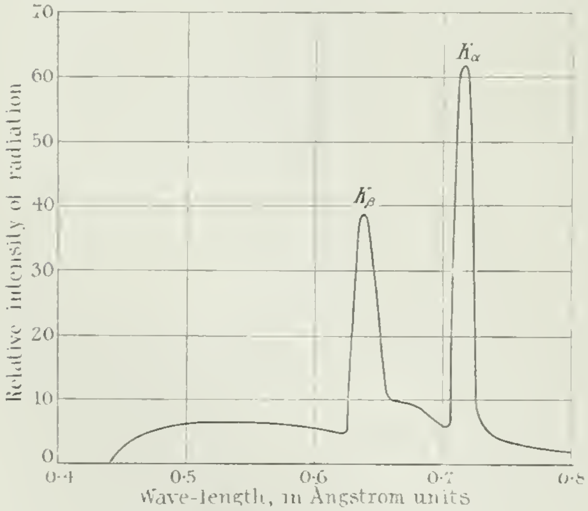


FIG. 4.—Molybdenum radiation.

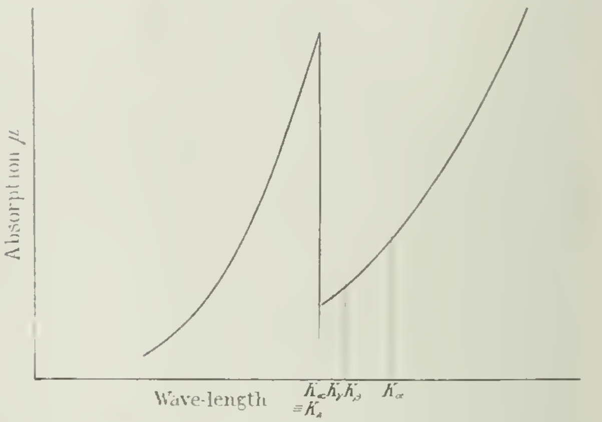


FIG. 5.—Ideal absorption curve, showing greatly increased absorption when the K radiation is excited.

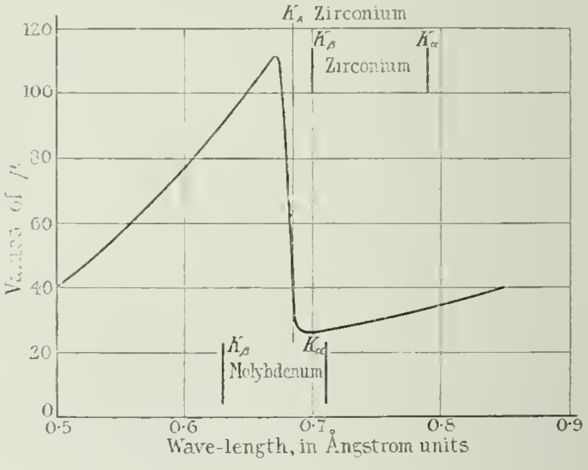


FIG. 6.—Absorption curve for zirconium, deduced from Hull's curves.

So far the radiation considered is the underlying continuous spectrum. Over and above this we obtain, under suitable conditions, radiation which is characteristic of the atom bombarded. Or, when radiation traverses a material, absorption may occur which is characteristic of the absorbing atom. The effects are almost exactly analogous to the emission and absorption of line spectra in light, brought about by exchanges of electrons between the various orbits or conditions in the atom (see Fig. 3). The outer orbits are those which function in optical phenomena; they are far from full, and exchanges of electrons between them take place readily. The inner orbits which function in X-ray work are, on the contrary, normally full and so exchanges are only possible when an electron has been ejected clear of the atom. Considering the inmost or K ring, an electron cannot be removed to the L, M or N rings because there is no vacant space. Line absorption is therefore impossible, except in extraordinary cases. Characteristic K absorption does not commence until the frequency of the absorbed radiation *exceeds* that associated with the K ring. When it does commence, the total absorption increases greatly. Similarly, K characteristic radiation is not excited until the voltage exceeds the K quantum limit. Then electrons may be ejected from the K ring. The restoration of the original state may be produced by a number of jumps on the part of electrons, giving rise to line emission.

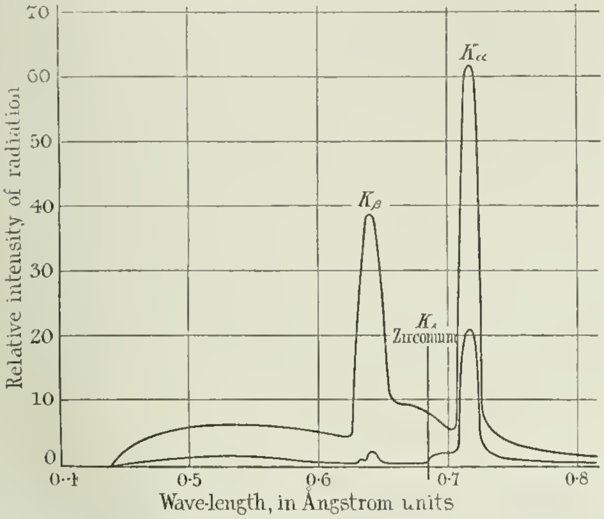


FIG. 7.—Molybdenum radiation before and after filtration through 0·35 mm of zirconium (after Hull).

Fig. 4 shows the characteristic radiation emitted by a molybdenum target at 28 000 volts (the quantum voltage is 20 000). The sudden increase in absorption at the K limit is illustrated in Figs. 5 and 6. Its application to the securing of a moderately monochromatic radiation for crystal work is indicated in Fig. 7.

### ABSORPTION OF HIGH-FREQUENCY RADIATION.

In the radiography of metals it may be assumed that we are always using voltages in excess of the K quantum limit. (The critical voltages for iron and lead are respectively 7 100 and 90 000.)

If a beam of monochromatic radiation of intensity $\mathbf{I}_0$ fall upon a homogeneous substance it suffers the same fractional absorption for each unit of distance traversed. The intensity $\mathbf{I}_x$ at a distance $x$ below the surface is thus $\mathbf{I}_x = \mathbf{I}_o e^{-\mu x}$, where $\mu$ is the fractional fall of intensity per unit distance. It is usually more convenient to use the mass absorption coefficient $\mu/\rho$ instead of $\mu$ ($\rho$ being the density). The absorbed radiation may be divided into two parts, a fraction $\sigma$ which is scattered per unit distance, unaltered in frequency, and a fraction $\tau$ which is transformed and degraded, reappearing as radiation of different frequency—heat, fluorescent radiation and corpuscular radiation. So that $\mu/\rho = \sigma/\rho + \tau/\rho$. It is very desirable that we should know more of these two coefficients than we do at present if we are to predict the voltages required for very high penetrations. I shall attempt certain predictions later but they will be made with reserve. In general it may be assumed that in comparatively low-voltage work the transformed radiation is greater than the scattered radiation, but that the order is reversed at greater penetrations.

J. J. Thomson has investigated scattering on the electromagnetic theory and has shown that the amount should be independent of the wave-length and proportional to the number of scattering electrons per unit volume. The latter number is roughly proportional to the density, so that $\sigma/\rho$ should be approximately a universal constant. Its value, according to Hull, is about 0·12. Later work appears to suggest that the value is about 0·17 for the light elements when low-frequency radiations are employed, but that the value decreases rapidly for the heavier elements with high-frequency radiation. If this value were constant it would impose a limit beyond which it would be impossible to reduce the absorption coefficient; this would mean in practice that there would be a definite limit to the thickness of matter which could be effectively radiographed. For steel this limit would be 7 inches. Fortunately this does not seem to be the case; for $\gamma$ rays the value of $\sigma/\rho$ certainly falls to 0·05. More recent work by Compton (referred to later) suggests a modification of Thomson's theory when the wave-length is comparable with the electron radius.

Bragg and Pierce have shown that the mass transformation coefficient is proportional to the cube of the wave-length. This law is certainly obeyed closely down to 0·09 Å.U. Beyond that point it appears that the coefficient decreases even more rapidly.

Except for very hard radiations the absorption coefficient may therefore be expressed as $\mu/\rho = a\lambda^3 + b$, or $\mu/\rho = (c/E^3) + b$.

### RADIOGRAPHY.

Turning now to the actual problem of radiography—the obtaining of a shadow image upon either a screen or a photographic plate—we have to consider how the properties of the rays must be used to obtain the best result.

Only those rays which pass through unaltered and undeviated contribute to the production of an effective image. All scattered radiation which penetrates only helps to fog the plate and mask the image. It is the object of efficient radiography to obtain as large a undeviated radiation as possible (to render exposures reasonably short), at the same time keeping down the scattered radiation. When the illumination due to scatter is rendered sufficiently small it is surprising what contrast can be obtained if the technique is correct. Surface scratches on a block of metal producing only the minutest variation of thickness show up quite distinctly on a radiograph. The reasons for this were pointed out by Sir William Bragg some time ago, although I think that with modern X-ray plates the sensitiveness is even greater than he suggested.

If we consider a scratch upon a piece of material, or a flaw in the interior, to be equal to a reduction of the thickness from $D$ to $D\text{-}d$, the strengths of the emergent beams are $\mathbf{I}e^{-\mu D}$ and $\mathbf{I}e^{-\mu(D\text{-}d)}$. The ratio is $e^{\mu d}$. That is to say, it depends only upon the absorption in a layer of the same thickness as the scratch or flaw and not at all upon the thickness, $D$, of the material. Theoretically, the absorption can be controlled at will by varying the voltage on the tube. When the voltage is small, $\mu$ is large, and therefore great contrast is theoretically obtained with low voltages. In practice, excessive exposures would be required if $D$ is great and, to render the exposure reasonable, $\mu$ must be decreased by increase of voltage. The argument is also vitiated to some extent by the fact that there is always a certain amount of scattered illumination on the plate, and although this decreases with reduction of voltage it does not fall nearly so rapidly as the direct illumination. The contrast is therefore actually expressed by a ratio $(\mathbf{I}e^{-\mu(D\text{-}d)} + s) \div (\mathbf{I}e^{-\mu D} + s)$, which becomes unity when $\mu = 0$ and $\mu = \infty$. Contrast requires this expression to differ as much as possible from unity, and this occurs at a certain value of $\mu$ or, in other words, at a certain value of the voltage. The optimum voltage increases with the mass of matter to be penetrated.

When we are considering great thicknesses it becomes clear that the minimum size of a flaw which can be detected is roughly proportional to the thickness of material in which it occurs, for the length of exposure is roughly determined by $\mu D$. If $D$ be doubled, $\mu$ must be halved and so $d$ must be doubled to give the same contrast. For high voltages the increased X-ray efficiency of the tube allows $\mu D$ to increase somewhat, and the minimum size of flaw discernible is slightly smaller than is indicated by the foregoing reasoning.

But the ratio between the illuminations reaching the plate does not alone define the photographic result. Here both the plate and the skill and experience of the radiographer enter definitely into consideration. The final contrast is expressed by the varying transparency of the plate at various parts. The rays cause deposition of silver, and this deposition proceeds at a rate depending upon the intensity and quality of the rays. Suppose we consider, as Bragg has done, the transparency of the plate diminishing exponentially towards zero at different rates at two different parts of the plate (see Fig. 8). (The curves have been drawn for intensities of illumination in the ratio of 2 : 1.) The ratio of the transparencies increases indefinitely with time until the plate is completely blackened and useless. The curves show, however, that the negative is capable of magnifying the contrast considerably if a long exposure be given.

Modern X-ray plates exaggerate the contrast still more; the emulsion is very thick, and complete loss of transparency occurs before all the possible silver has been deposited. A plate which is not *completely* exposed will appear like a piece of ebonite after development. The transparency curves become asymptotic to an axis below zero (see Fig. 9). It will be seen that one part of the plate may be completely blackened while another is still reasonably transparent, and the contrast is thus practically infinite. I have not pushed the reasoning far. The curve in Fig. 9 is drawn for an emulsion 20 per cent thicker than the critical amount. It is seen that, even with this small increase, greater contrast is obtained without blackening the plate to the same extent.

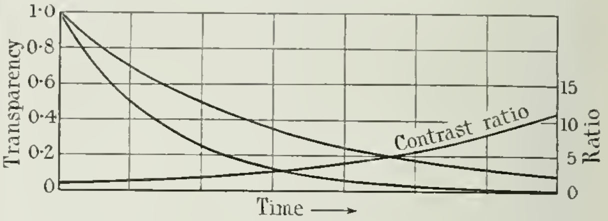


FIG. 8.—Showing the contrast obtained with an emulsion just thick enough to blacken completely with a long exposure.

This question of the emulsion is one which repays a great deal of attention. Although very notable work has been done in recent years we may hope for still further assistance in this direction. An ordinary photographic plate is of little use for very hard rays. Rays which have penetrated 2 inches of steel are rather scornful of 2 mils of emulsion. It is rather like trying to stop bullets with a tennis net. Further, the ordinary photographic plate is particularly sensitive to the low-frequency radiations, and so transformed radiations which reach the plate have considerable fogging capacity. Our problem therefore resolves itself into two parts, (i) eliminating as far as possible all radiations which do not contribute directly to the formation of the image, and (ii) making the plate as sensitive as possible to the high-frequency radiations.

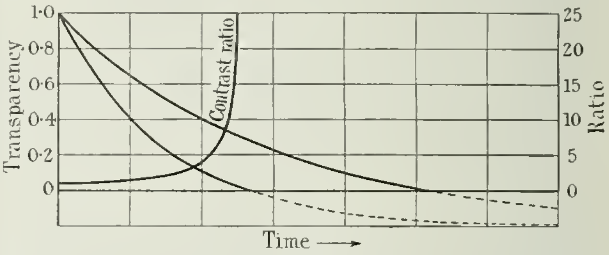


FIG. 9.—Showing the contrast obtained with an emulsion 20 per cent thicker than in the previous case.

Let us consider first the elimination of stray radiation. Suppose we wish to radiograph an object which calls for a moderate penetration, using rays which are projected vertically downwards. The plate is placed first upon a thick sheet of lead—this is to absorb radiation which passes through the plate and to prevent it being fogged by scatter from below. The object is then placed upon the plate and if it is regular it is completely surrounded by lead so that no radiation can possibly reach the plate except through the object to be radiographed (see Fig. 10). If the body is irregular it is mounted on plasticine trimmed flush with the edge ; lead dust to a depth of several millimetres is then distributed round it. The exposure is then made. (When the penetration attempted is considerable, the advisability of backing the plate with lead is doubtful. The particularly penetrating characteristic radiations of lead are excited and cause a certain amount of fogging. A lighter backing such as iron will often give better results.)

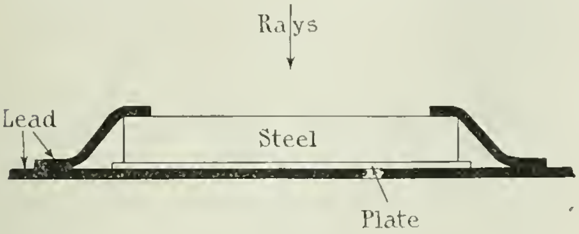


FIG. 10.

In addition to the undeviated radiation there is, of course, the scattered and transformed radiation which passes through the material. The distinguishing features of this radiation are that it is distributed in all directions and is largely composed of very low-frequency rays. The Potter Bucky diaphragm attempts to eliminate a considerable fraction of it by cutting out all that is not sensibly parallel to the incident beam. The low-frequency radiation may be reduced in relative effect by rendering the plate more sensitive to the high-frequency radiation. It appears also that the low-frequency radiation might be largely eliminated by a thin sheet of moderately absorbent material placed above the plate. Lead foil has been used in such a position for reinforcing the radiation, although its use below the plate is much more common. I do not know that it has been used generally for the purpose suggested.

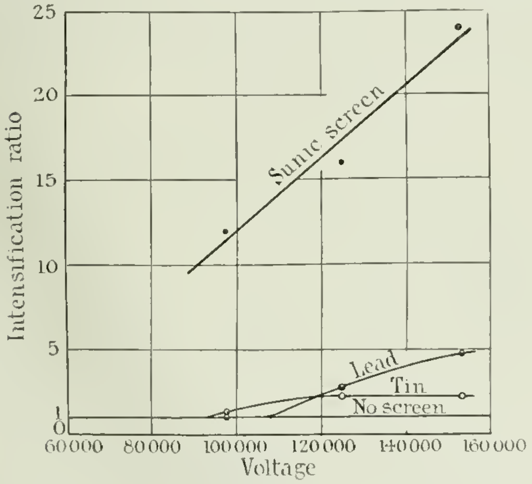


FIG. 11.—Showing intensification produced by various screens.

Much reduction in exposure can be effected by the suitable use of intensifying screens and by increasing the absorptive power of the plate or film. " Duplitized " films having a layer of emulsion on both sides are commonly used. Oxides of lead and thorium are often added to the silver bromide to increase the absorptive power of the emulsion. In addition, intensifying screens of calcium tungstate placed in contact with the film produce a similar effect. The modern Impex plate is practically a plate plus screen made in one unit ; the screen is dissolved off after exposure. It is also common to place a sheet of lead foil immediately behind the film ; high-frequency radiation which would otherwise be lost is thus made to produce the characteristic radiation of lead, which strikes back upon the film. Fig. 11 gives the results of a series of experiments carried out at Woolwich upon the efficiency of various screens.

### LIMITS OF PENETRATION.

As has been indicated earlier, the greater the mass of substance to be penetrated the higher is the optimum voltage for good definition. In addition, exposures are greatly reduced at high potentials. Fig. 12 illustrates the penetration of $\frac{1}{2}$ cm of copper at 100 000 volts and at 200 000 volts.

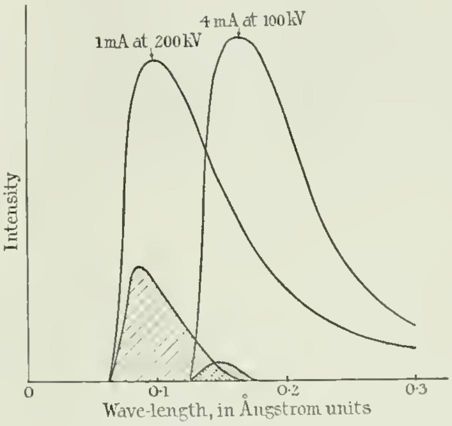


FIG. 12.—Diagram showing greater penetration at higher potentials. Penetration of 0·5 cm of copper.

It is commonly stated that 3 inches of steel is the present practical limit of penetration. I think that that is rather a conservative estimate but we will assume it for present purposes. It is clear that if greater thicknesses are to be penetrated we must increase the voltage so that the amount of radiation penetrating the material remains constant. This allows $\mu D$ to increase slightly with voltage. The relation between $\mu$ and $E$ has been expressed as $\mu/\rho = c/E^3 + \sigma/\rho$. How this relation changes for really high values of $E$ is uncertain. The first term apparently decreases still more rapidly and $\sigma/\rho$ begins to fall as $E$ is increased.

Compton * has investigated theoretically the variation of the transformation and scattering coefficients at high frequencies, on the assumption of a ring electron of radius 0·02 Å.U. His conclusions agree well with the experimental data available. Figs. 13 and 14 have been prepared for iron on his assumptions. It will be seen that for low voltages $1/\mu$ is roughly proportional to the cube of the voltage, but that the form of the curve changes rapidly above 200 000 volts, when $1/\mu$ becomes approximately proportional to the potential. At the higher voltages the X-ray efficiency of the tube increases and the penetration for a given power increases more rapidly than the reciprocal of $\mu$.

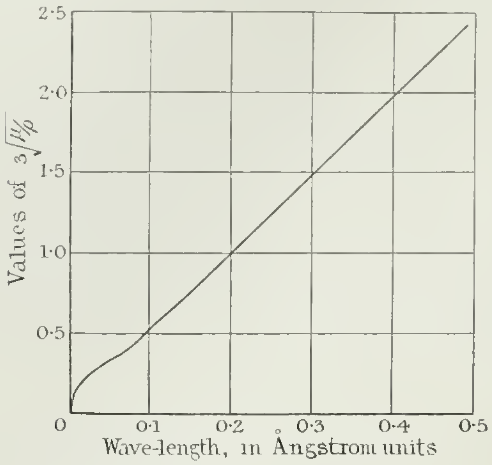


Fig. 13.—Absorption in iron.

When penetrating 3 inches of steel at 200 000 volts $\mu D$ is equal to 3; $e^{-\mu D} = 0·05$. That is to say, of the hard radiation emitted by the tube 1/20th penetrates the specimen. There is, of course, a large amount of soft radiation in addition, but this is of no importance from the radiographic point of view.

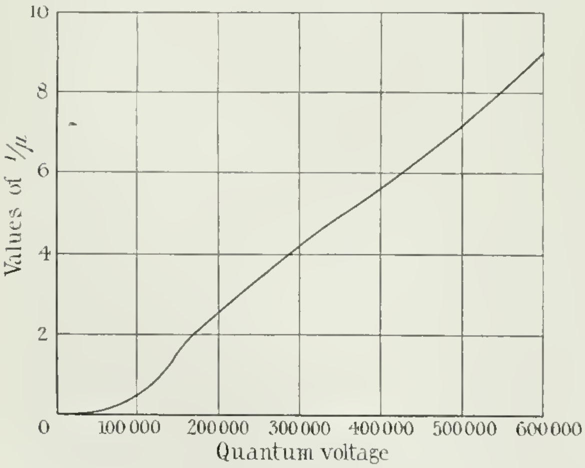


Fig. 14.—Absorption in iron (hardness of rays defined by quantum voltage).

It is usually believed that the X-ray output of a tube may be expressed as $I_0 = KIE^2$, where $I$ is the current and $E$ the voltage. As the potential rises, the increase in output is accompanied by a relative shortening of the wave-length of the peak of the radiation curve. As in radiographic work one is only concerned with the hardest part of the spectrum, the assumption of the above relation as a basis of calculation is distinctly conservative. The calculations and curves are given with reserve but it is believed that when the voltages and currents assumed are attained, the results will not fall short of those predicted.

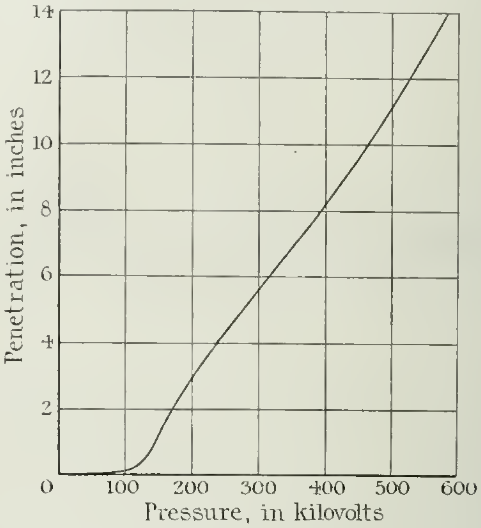


Fig. 15.—Penetration of steel with 0·6 kW in the tube.

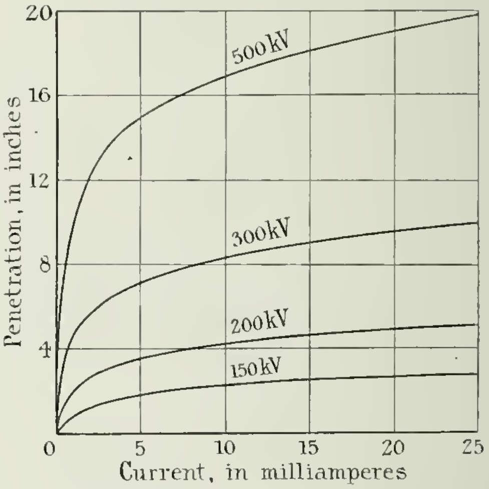


Fig. 16.—Penetration of steel.

There are three possible directions, each of very distinct promise, in which improvement may be attempted :—

(1) The tube may be constructed to stand a higher voltage ;

(2) It may be designed to carry a heavier current ; or

(3) The sensitiveness of the plate may be increased.

---

* *Physical Review*, 1919, vol. 14, ser. 2, p. 20.

If the sensitiveness of the plate be denoted by $s$, the photographic result may be denoted by $P = AsIE^2e^{-\mu D}$. It is clear that increase of current and improvement in the plate are equally effective. Increase of voltage produces a much greater effect, not only on account of the square-law variation with $E$ but also because $\mu$ decreases when $E$ increases. It is, however, probably easier to increase the current-carrying capacity of the tube than to increase its ability to withstand a high potential.

Leaving the plate out of consideration, the photographic result is determined by $IE^2e^{-\mu D}$, whence $\mu D = 2 \log E + \log I + C$. If we assume a tube of the Coolidge type where the power is defined, i.e. $\log E + \log I$ is constant, we obtain $\mu D = \log E + K$, which for steel becomes $\mu D = \log (E/200\,000) + 3$. If we assume that 3 inches is the practical penetration at 200 000 volts when the tube is carrying 3 mA, we obtain Fig. 15, which gives the penetration possible at various voltages up to 600 kV.

If, however, it is possible to increase both $E$ and $I$, families of curves such as those given in Fig. 16 are obtained. Deep penetrations become possible when we are able to construct tubes either for very high voltages or for very high powers.

### X-RAY TUBES.

To turn now to the outfit for the production of X-rays, we require in the first place a source of electrons and in the second a source of high potential. Two methods are in common use for the production of electrons: (1) their evaporation from a hot filament, as in the Coolidge tube, and (2) the bombardment of the cathode by positive ions, as in the gas tube.

For a long time the gas tube has held the field and there are still many who maintain that it is capable of giving better results than the Coolidge tube. This claim will be examined later. Figs. 17 and 18 show standard types of gas tubes. It is not necessary for me to enter into detail concerning the exact nature of the discharge. Much has already been said and written upon that subject, but there is still much that we do not understand. I would, however, draw attention briefly to some important experiments by Ratner, the results of which were published about a year ago.* It is quite clear that if the discharge through a gas tube is to be maintained, every pair of ions must on the average, before they go out of existence, give birth to one other pair. Now at the vacua that exist in these tubes it seems hardly probable that the ions in their journeys towards the electrodes would encounter molecules sufficiently closely and sufficiently often for them to produce ions numerically equal to themselves. In fact, Ratner found that under certain circumstances the gas pressure could be as high as 100 bars and yet no discharge would take place at 50 000 volts. It appears that the absorbed layer of gas upon the cathode plays a very important function—that it is the bombardment of this semi-conducting layer which provides the necessary corpuscles. A positive ion dashing into this layer may release a cloud of electrons, and the discharge is continued if *one* of these collides with a gas molecule sufficiently vigorously to ionize it. The bulb may become polarized and refuse to pass current when this layer is removed, even though the gas pressure in the bulb is high. The tube will still conduct well if the voltage is reversed. It cannot be said that Ratner's experiments explain all the facts, but they take us distinctly nearer to a solution.

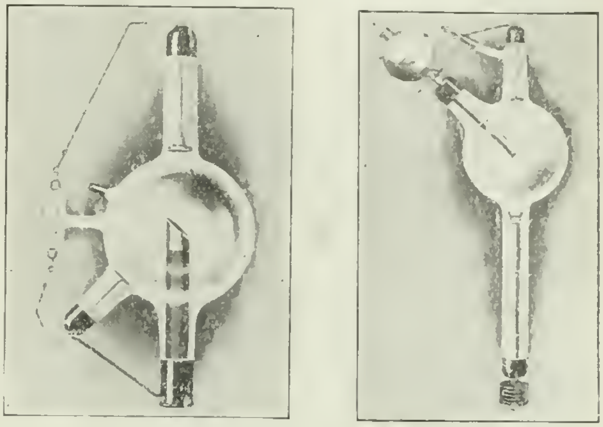


FIG. 17. FIG. 18.

Typical modern English gas tubes.

Gas tubes tend to get harder with use. Part of the effect is temporary and is to a great extent explained by Ratner's results. But in addition there is a permanent hardening action, to overcome which means must be provided for admitting gas to the tube at intervals. The pressure in a gas tube is never very low—about 1 to 10 bars.

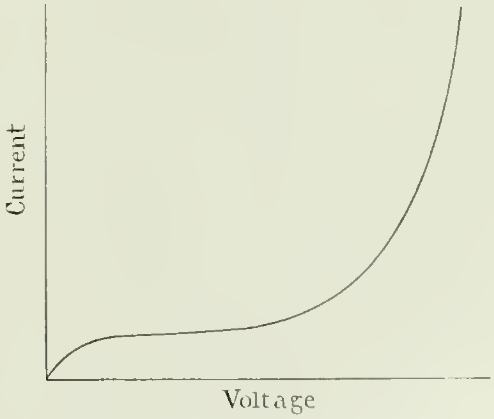


FIG. 19.—Relation between potential across, and current through, a gas tube.

The relation between the voltage across a gas tube and the current through it depends enormously upon its state of exhaustion, and, as has already been indicated, the hardness of the tube varies considerably. But the general relation between voltage and current is of the nature indicated in Fig. 19. The voltage and current cannot be varied independently.

Despite the fact that many workers proclaim the advantages of the old-fashioned gas tube, modern technique in general demands the more controllable hot-cathode tube. Fig. 20 shows the Coolidge tube. In this the electrons are provided by an incandescent tungsten filament. The vacuum is much better than in a gas tube, the pressure never being greater than 1/10th bar and more often being 1/100th or 1/1 000th bar. The remaining gas takes a negligible part in the discharge. The voltages that occur in X-ray practice are such that saturation current is always obtained. That is to say, the current through the tube is controlled entirely by the filament temperature and is independent of the voltage at which the tube is worked. Either a filament transformer or suitably insulated batteries may be used for the current supply.

---

* *Philosophical Magazine*, 1922, vol. 43, p. 193.

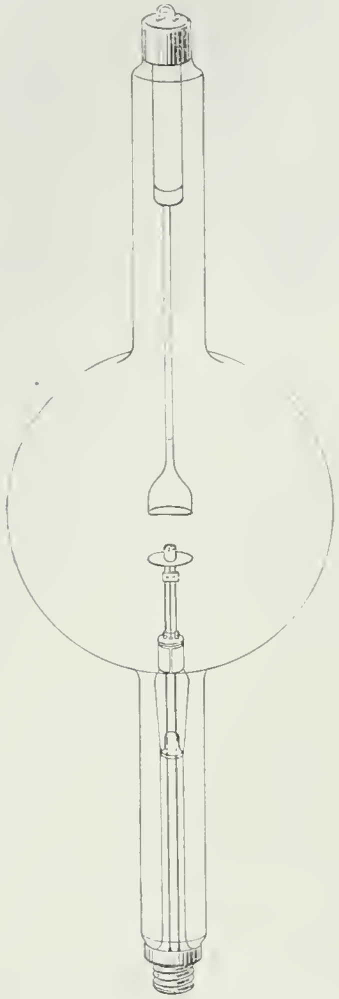


Fig. 20.—Coolidge standard tube.

The differences in the behaviour of gas tubes and hot-cathode tubes would appear to be explained simply on the basis of the voltage/current characteristics. The potential applied to a tube is unfortunately nearly always variable. Under such conditions the bulk of the current through a gas tube is let through at the highest voltage, whereas in a Coolidge tube it is let through uniformly. One would therefore expect a greater radiographic result with a gas tube working at the same voltage and average current. It happens that one disadvantage of the gas tube, among other things, partially counteracts the effects of an inefficient high-voltage supply. The obvious development is to improve the high-tension system.

For general radiological purposes the desiderata for a target are: High atomic number, high melting point, low vapour pressure, high thermal conductivity and high specific heat. Tungsten fulfils these requirements better than any other metal.

In the standard Coolidge tube the target is a solid block of swaged tungsten. This may be worked white-hot in the tube; when it can dissipate continuously over 1 kW by radiation. The light emitted from the target under these conditions is intense and the bulb resembles an arc lamp. The electron emission from the target is considerable and all inverse voltage must be suppressed, otherwise electrons are driven in high-velocity streams to the glass, quickly cracking it.

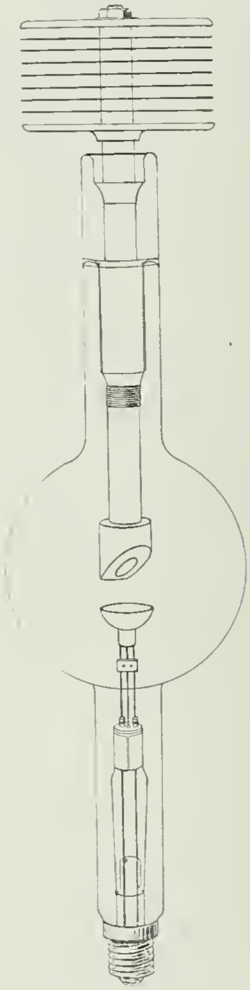


Fig. 21.—Coolidge radiator tube.

Fig. 21 shows the radiator type of tube. The target consists of a tungsten button about which copper is cast. The copper continues as a rod through a platinum seal to an outside radiator. The tube is only suitable for small powers—about $\frac{1}{4}$ kW continuously—but under such conditions it can be used with unrectified alternating current. The target never rises sufficiently in temperature to give any sensible emission of electrons.

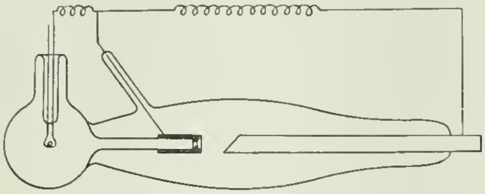


Fig. 22.—Essentials of Lilienfeldt tube.

The Coolidge tube is a diode. The Lilienfeldt and Müller tubes are triodes. Fig. 22 shows the former. In it the current is controlled by the potential of the "grid"; in the Müller tube (Fig. 23) it is controlled by the magnitude of the "grid leak." In any hot-cathode tube the voltage and current can be varied independently.

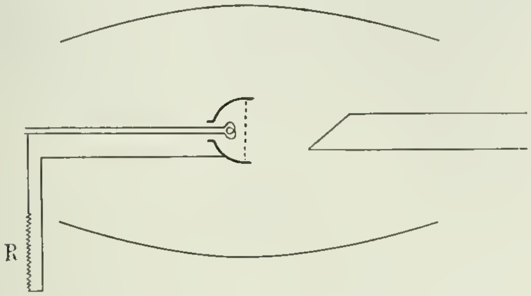


Fig. 23.—Scheme of Muller tube.

### Focusing.

In a gas tube the focal spot is liable to wander and to depend in size upon the state of the vacuum, the voltage across the tube, and the current through it. It is, in fact, largely controlled by the space charge, which in ionic conduction is positive. This evidences itself by the bulk of the glass being positively charged. A positive space charge of course tends to open out the cathode stream. In the Coolidge tube the space charge is negative and the glass, as has been shown by Thomas,* differs only slightly in potential from the cathode until the anode arm is reached. The space charge is far more definitely related to the load than it is in the gas tube, and the size of the focal spot can be accurately predetermined by the position of the filament in the hood. When the filament is far in, the focus is fine (see Fig. 24); when it is near the aperture the focus is broad (see Fig. 25). A pinhole X-ray photograph of a broad focal spot designed for gas ionization work clearly demonstrates the projection of the electrons as a spiral sheath towards the target, as suggested in Fig. 25, and the X-rays are emitted from an enlarged image of the filament.

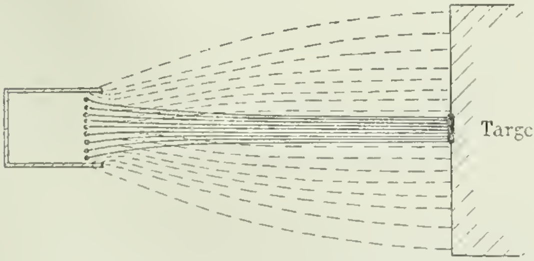


Fig. 24.—Diagram illustrating fine focus.
Broken lines indicate lines of force.
Full lines indicate cathode streams.

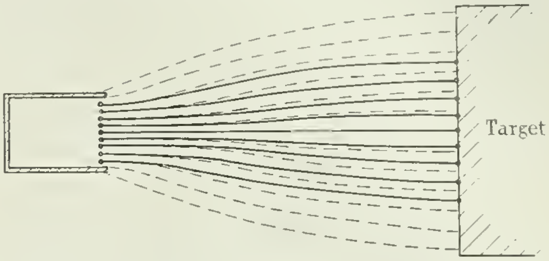


Fig. 25.—Diagram illustrating very broad focus.
Broken lines indicate lines of force.
Full lines indicate cathode streams.

### Gas in the Tube, and Sputter.

A thoroughly exhausted Coolidge tube should show no sign of fluorescence whatever. Fluorescence is due generally to bombardment of the glass by electrons; this should not be able to take place to any degree unless parts of the glass are being periodically charged positively by positive ion bombardment. In consequence of the comparative lack of bombardment, the glass of a hot-cathode tube keeps much cooler than that of a gas tube.

The vacuum in a Coolidge tube tends to improve just as a gas tube tends to get harder. Positive ions when formed are driven to the glass and many of them penetrate to a depth which prevents their release. With a certain amount of gas in the bulb the amount of fluorescence is dependent on the load. It is greater the heavier the current, as would be expected, but often it will disappear at high voltages. Probably this is due in the first place to the fact that the high-velocity electrons are not nearly so effective in ionizing the gas, and secondly, the gas that is ionized is driven with such velocity to the glass. I have seen a tube show very marked gassing at 100 000 volts and yet work reasonably well at 200 000 volts. The gas will also often disappear if the target be run really hot. This is probably due to the getter action of incandescent tungsten.

A tube worked in a gassy state tends to become sputtered. A certain amount of coating of the glass with tungsten cannot be avoided if the target is worked at white heat. This is simply evaporation. But, apart from this, the ionic bombardment of the cathode results in actual fragments being knocked off, and these find their way to the glass. This cathodic sputtering occurs in definite rings or zones—or rather there are definite rings where sputtering is comparatively absent. We have found that these unsputtered areas are those which are bombarded by cathode streams. The cathode particles are negatively charged and will not stick to the areas subjected to electronic bombardment.

---

* See R.D. Report, No. 52.

Sputtering assists in improving the vacuum. The effect may be partly chemical but it is certainly partly mechanical. Gas which is plastered on the glass may be trapped by depositing a film of metal upon it.

### Electrical Equipment.

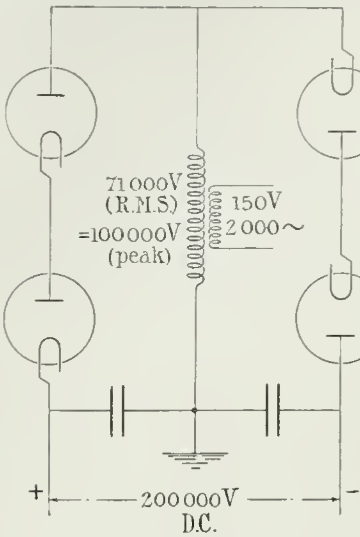


Fig. 26.—Coolidge and Hull's connections for high-tension d.c. supply.

The greatest problem in the electrical equipment is the high-tension supply. What is desired is a steady direct voltage; but that can rarely be obtained. It is extremely desirable that for the period that the pressure is applied it should be maintained as close as possible to its maximum value. Any pressure lower than the optimum voltage for the work in hand produces heat with little radiographic result. When attempts are being made to secure high-frequency monochromatic radiation, the production of any excess of low-frequency radiation is directly objectionable. When the voltages are very low, e.g. for spectrometric work, batteries or a d.c. generator may be used. One particular set which I saw in Tokio some 7 years ago consisted of three 5 000-volt generators connected in series. But a limit is soon reached in this direction and the direct generation of the d.c. voltage cannot be considered at present for general work. High-tension electrostatic machines have been used for low-current tubes, but at present they are not very practicable. For small powers the induction coil is perhaps the simplest solution. It involves no running machinery except the turbine interrupter. But when that has been said there seems little remaining in its favour. The voltage is extremely variable; on no load the inverse pressure approximates to the forward pressure, and on load exceeds it.

Undoubtedly the best solution up to the present is based upon the method used for obtaining a d.c. supply in wireless work, i.e. by charging condensers from an a.c. supply rectified by thermionic valves. The simple but ingenious connections used by Coolidge and Hull are shown in Fig. 26. Four kenetrons, each capable of withstanding 100 000 volts, are involved, together with their filament transformers, and high-tension condensers capable of withstanding 100 000 volts each, in addition to the 2 000-period alternator. Such an outfit must be expensive, comparatively inefficient, and costly in renewals. In addition, the number of high-potential points is very considerable.

For some time, at any rate, the most general outfit will consist of the so-called "interrupterless" machine. This is simply a high-tension a.c. transformer with a mechanical rectifier. The function of the latter is not only to rectify the high-tension voltage but also to connect the transformer to the tube only near the peak of the voltage wave. The rectifier may be driven by a synchronous motor, but undoubtedly the system works better when an inverted rotary converter is used for the low-tension a.c. supply, with rectifying discs fixed upon the rotary shaft. Hunting is the trouble with the small $\frac{3}{4}$ h.p. synchronous motors. It is, I believe, imagined by many radiologists that the transformer, rectified in the manner indicated, gives a more or less uniform potential across the tube. This is not the case: high-frequency oscillations of considerable amplitude are produced. Fig. 27 shows approximately the magnitude of the potential variations for a typical load.

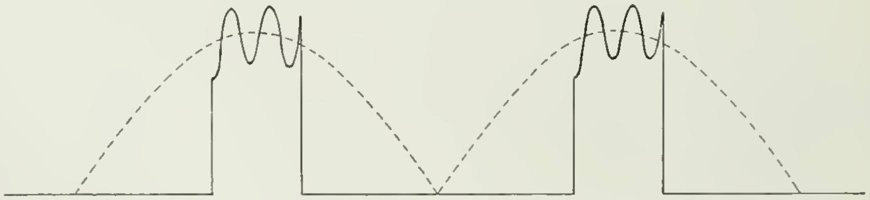


Fig. 27.—Diagram illustrating the nature of the voltage wave applied to an X-ray tube (drawn to scale for a typical load on a standard type of transformer).

Fig. 28 shows a transformer designed and constructed in the Radiological Laboratory at Woolwich Arsenal. This is designed to give 30 mA at 150 000 volts continuously (X-ray rating). A transformer of this size would be capable of giving 9 kW continuously under ordinary a.c. conditions. Contact is usually made for about one-quarter of the time, so that 30 mA really means 120 mA for the time during which the tube is being operated; this is equal in heating value to 60 mA (R.M.S.).

For a great deal of work in the future it may be possible to construct the whole outfit as one unit. The transformer need have no expensive terminals but can be connected through its rectifier to the tube working in oil. The set can be reduced to a box with a couple of terminals between which a pressure of 250 volts is applied, the resulting X-rays passing through a suitably disposed aperture.

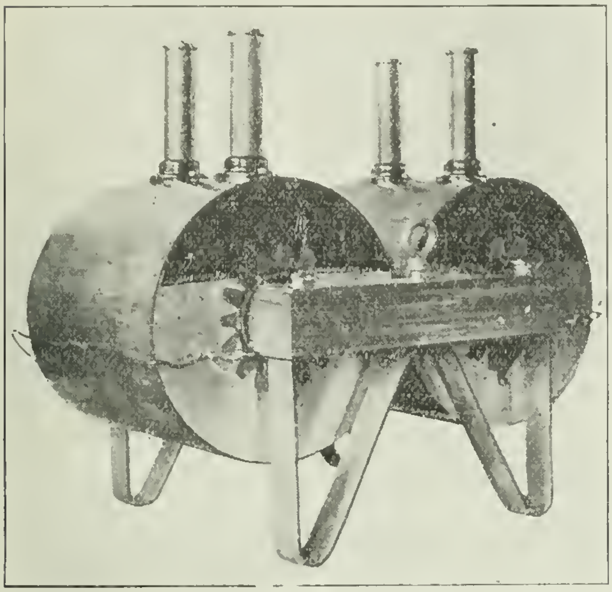


FIG. 28.—Transformer to give 30 mA at 150 000 volts (X-ray rating). Particular construction eliminates metal tank and simplifies the terminal problem. The secondary coils only are oil-immersed. (Described in R.D. Report No. 56.)

The voltage control may be effected either by an auto-transformer or by a resistance in the primary circuit. The latter, in spite of its inefficiency, possesses distinct advantages when the power wasted is not too costly. Personally, I am inclined to favour a combination of the two methods. Resistance may undoubtedly save the tube in the case of a sudden evolution of gas, and may even enable a gassy tube to be run more or less satisfactorily. It may, however, produce risks of its own if carried too far.

### CONCLUSION.

In this hurried survey of the subject I have attempted to indicate the lines along which progress may be expected. I have said little of the difficulties with which we are faced, but if I have aroused interest in some of the problems I shall have achieved one object.

At the present moment the X-ray tube is a very useful tool, within its limits. I am convinced that research will extend the field of application very considerably. There are always those critics who say: "Three inches of steel! That is no good, we want six." And when they have six inches they will want twelve. I think that they will get their six inches and probably their twelve. It has, however, been said that there is no physical possibility of obtaining these penetrations. I have tried to answer that criticism, which is, I believe, founded upon fallacious reasoning around wrong data.

In conclusion I should like to acknowledge the assistance which I have received in the preparation of this lecture, from the Director of Radiological Research and from my colleagues at Woolwich. Much of the material I have placed before you has, of course, been borrowed from many sources, but where I have been able to present new facts or a new light upon old ones, the above-mentioned have been largely responsible.

# DISCUSSION ON
# "VARIABLE-SPEED ALTERNATING-CURRENT MOTORS WITHOUT COMMUTATORS."*

WESTERN CENTRE, AT SWANSEA, 7 MAY, 1923.

**Mr. J. W. Burr:** The author in his introductory remarks stated that "It has become sufficiently clear during the past few years that the polyphase alternating-current system will ultimately be universally adopted for power supply on a large scale." In my opinion it will not be many years before the generation of electricity is centralized in the country, in which event it would appear that the author's statement is likely to be correct. At the present time many collieries and other power users have installed direct-current motors because of the flexibility of control. In some cases they still think that the alternating-current motor is not suitable for their purpose and prefer, in the event of taking a supply from a distributing authority, to install rotary converters and sacrifice considerable efficiency instead of changing their motors. I think, however, that if an alternating-current motor without commutator were available, one capable of gradual speed variation from one end of the range to the other without continuous loss of power at any speed, these particular consumers would change their views. The method of controlling the speed of the induction motor would obviously be by changing the number of poles or the frequency of the supply, since the speed of any induction motor depends upon the frequency and the number of poles. The difficulty always appears to me to be one of changing from one step to another without mechanical shock to the motor and electrical shock to the system. It has always seemed to me that the method of varying the speed by altering the number of poles was likely to cause the effect that I have just mentioned. It would appear, however, from the author's remarks that smoother running through different speeds is obtainable by changing both the number of poles and the frequency of the supply. The method of changing the phases by means of transformers has, of course, been usual for a number of years in connection with rotary converters. It would appear that if attempts to change the number of phases with the machine running were made, very complicated and expensive switchgear would be required. This seems to be a difficulty which must be overcome. I was very interested to see that the efficiency remains very nearly the same at all speeds. The power factor curve, however, does not ascend as rapidly as the efficiency curve, due, as the author points out, to the fact that the magnetizing current remains the same at all speeds while the true power output falls off proportionately to the reduction of speed. I should like to know whether or not it is possible to reduce the magnetizing current at the low speed so as to improve the power factor; this is, in my opinion, a most important matter. I am sure that many members present will be interested to know that a cascade set can be used for the purpose of improving the power factor. There is no doubt that the chief drawback to synchronous sets is their high cost, and, in my opinion, any combination which will improve the power factor and is reasonable in first cost will be welcomed by many colliery and works engineers.

**Mr. R. G. Isaacs:** The majority will, I think, agree with the author that there is a great need at the moment for a satisfactory variable-speed alternating-current motor. It is well known that induction motors are used in cases where variable-speed motors will give greater economy or better results. A winding giving a different number of poles by altering the number of phases is, of course, not absolutely new. For example, on the Italian State Railways a motor has been used in which by changing the number of phases from 3 to 2, the number of poles is changed from 8 to 6, giving a corresponding change of speed. That is, of course, a special case and one could only guess at the patient research necessary to evolve the winding described in which, with a moderate number of terminals, four speeds were obtained. The author has produced a motor which I am sure will be of great use in many electrical drives. In connection with the power factor of these machines I cannot quite agree with the author that it is the amount of magnetizing current and not the power factor that has to be taken into account. The power factor must be of importance when there is a power factor clause in the tariff. Low power factors are often due to under-loaded induction motors; in many cases light loads are taken at reduced speeds. Would it be possible to use this cascade type of motor, running as an induction motor at full load and full speed, and as a synchronous motor at unity power at the reduced speed? It occurred to me that if we were to use a small commutating machine connected to the author's motor we should have a continuously variable-speed motor that would be very much cheaper than the usual Kramer type. The flaw in this scheme apparently is that with the present winding it is only possible to get slip-ring control on one speed. In his reply at one of the other centres the author referred to slip-ring control on each speed. Did he mean that it is now possible to have it on each speed? We have now a fairly wide choice of alternating-current motors of various kinds, but the newer types have not yet come to that place in industry to which they are probably entitled. I think that the reason is largely that the average man does not care to tackle something with which he is not quite familiar, and in this connection I think that the manufacturers would benefit considerably if, by loaning machines to colleges, they make it easier than it is at present for students to become familiar with the operation of the new types. The author has opened up a wide field for thought and one that has not yet by any means been fully explored.

---

* Paper by Mr. F. Creedy (see page 309).

**Mr. D. Jenkins :** The motor described in the paper is best considered in the light of its applicability to the conditions obtaining in this district, where the chief use for a variable-speed induction motor is for haulage work in collieries. As most of these haulage motors are installed underground, they and their control gear must comply with the Mining Regulations, in most cases with the notorious Clause 132. The complex controller shown on the lantern slide would have to be greatly modified to comply with the Mining Regulations. Not only does the complexity of the controller make that a very difficult matter, but the multiplicity of the terminals on the motor controller, phase converter and the interconnecting wiring would make such modification of design almost impracticable, and I fear that for this reason alone the colliery electrical engineer will not approve of the equipment. In Swansea the frequency of practically every colliery supply is 50. With this frequency the synchronous speeds available are 3 000, 1 500, 1 000, 750, 600, 500, 428, 375 r.p.m., etc. It is seen then that the difference between successive synchronous speeds is very high at the top of this range, and for this reason I imagine that the multiple-speed motor will be chiefly used at low speeds. Otherwise speed variation would be possible only with heavy rotor losses; in other words, the utility of the multiple-speed motor will be found in those conditions which involve a low power factor and high cost, and for this reason its usefulness will be limited. Much research work has been done during the past few years on the question of variable-speed a.c. motors, but, in spite of the distinct advance made by the author's multiple-speed induction motors, it is still doubtful whether a satisfactory electrical solution to the problem is possible. The induction motor is essentially and inherently a constant-speed machine and hitherto it has been impossible to obtain with it a speed regulation of anything like the efficiency and range obtainable with a direct-current shunt motor. For this reason one has almost come to the conclusion that the solution is to be found in introducing a variable-speed coupling between the induction motor and its drive. Such a coupling was to be found in, say, the Williams-Janney variable-speed gear. With such an equipment the induction motor would always run at its full speed and, therefore, at its maximum power factor. It would not be required to reverse, and might be of the squirrel-cage type. Even a synchronous machine could be used. One of the lantern slides exhibited a curve showing the comparative cost of the multiple-speed and the standard induction motor. Do the prices include the control gear required in the two cases, i.e. do they include the multiple-speed machine with its controller and phase transformer on the one hand, and the standard induction motor with its standard starter on the other? Another lantern slide showed the power factor performance of a multiple-speed machine designed to run at 187 r.p.m. and 125 r.p.m. and to give an output of 860 h.p. at the former speed. The power factor read from the curve was 0·6 leading. This seems extraordinary high, but this power factor was obtained at the lower of the two speeds when the motor gave an output of, I think, only 250 h.p. The percentage reduction in the horse-power is very much less than the percentage reduction in the speed and it would appear as if the motor gave such a good power factor at the lower speed only in view of the reduced output, i.e. the motor could be adjusted to take a heavy leading current only at the expense of a low load current. This, of course, could be done by any other standard synchronous induction motor.

**Professor F. Bacon :** The new windings discovered by the author strike me as being a very notable achievement in this intricate field of research. I should like to ask the author what methods he employs to discover new windings. It is only by actually experimenting with such motors that students will gain familiarity with their behaviour and confidence in their capabilities, and on that account I would urge the plea, already raised by Mr. Isaacs, that it would pay manufacturers to help the colleges to acquire small induction motors of these new change-pole and cascade types. The author, I imagine, considers that he has knocked some more nails into the coffin of direct current. We should feel in a better position to judge of this if he would give a list of concrete examples of drives for which he would definitely recommend his motors. Battleships, for example, have remained a stubborn stronghold of direct current. Does the author think that his motors will tip the scale in favour of the use of alternating current on warships? Here is a field where the very best is reckoned none too good and where cost is only a secondary consideration. On the other hand, weight and space are very precious. The paper contains no reference to electric traction. Are we to infer that the author does not see a future for his motors in this direction? On page 310 planing machines are bracketed with boring mills. This appears to need a little further explanation as, unlike the case of the boring machine, it is the frequency of reversal (and not the speed) in the case of the planing machine which has to be varied to suit the size of the job to be machined.

**Mr. T. H. Haigh :** I am particularly interested in 25-period plant. Does not the author think that his motors would be seriously handicapped on this periodicity due to the very limited number of reasonably useful speeds available?

**Mr. J. C. Howell :** Economical variable-speed alternating-current motors are very desirable things to have, especially in this district, and I had hoped that the author had succeeded in designing a machine which would automatically vary its speed in accordance with the load to be dealt with. It is a disappointment, therefore, to find that at the present time variable-speed motors are limited to six distinct steps, with a hand-regulated commutator device to bring about each successive step, a method that could not be advantageously employed in, say, rolling-mill work with heavy flywheels for dealing with peak loads. I hope that the author will continue his research work until he has evolved the continuously variable-speed alternating-current motor for which engineers are waiting.

**Mr. K. B. Ashton:** A previous speaker, interested in the distribution of alternating current, suggested that the author had driven another nail into the coffin of direct current, and, as the title of the paper itself implies that a commutator is an undesirable feature, it is only fair to state that in this district where so much direct current is in use the experience in local works is that direct-current motors are at least as reliable as induction motors and that modern commutators give no more trouble than slip-rings. In the case of rolling mills a compound-wound motor can be arranged to give the 10 per cent drop in speed at full load necessary to take advantage of the flywheel effect, as a normal characteristic of the machine and without the use of automatic switchgear. In the case of driving turbine and centrifugal pumps a direct-current motor has also the great advantage of allowing the slight increase of speed necessary to overcome the increased friction in the piping due to ageing. Alternating current appeals chiefly to the distributing engineer, and local works will not be tempted to change from direct current until an alternating-current motor is developed with the characteristics of either series, shunt or compound-wound d.c. machines. When it is considered that even then it would be necessary to give unity power factor with large air-gaps to be on the same footing as direct current, it will be seen how much further scope remains for invention.

**Mr. C. T. Allan:** I am interested to learn that these motors give a leading power factor at low speeds. The subject of power factor is increasingly engaging the attention of all supply engineers, and power factor has to be counteracted in tariffs by charging on a kVA basis. For large consumers, owing to motors being purchased somewhat too large for their work and due to these being seldom fully loaded and practically never overloaded, the system power factor tends to fall. Even the increasing number of very small motors in shops, etc., has the same effect, and it might possibly be worth while to offer special inducements to consumers to install high-power-factor motors of the Creedy type. Are 25-period motors of the type in question much more expensive than 50-period motors? In regard to haulage motors, I should like to inform the author that the maximum size instead of being 50 h.p. is often 300 h.p. and even higher. Could such motors be used without transformers on 3 000-volt circuits? There would very possibly be an extensive field for the author's motor if it could be built in sizes up to 3 000 h.p. Has the author used this type of motor for driving boiler fans? It appears to me to be a field that would well suit it, and would enable the draught to be forced or reduced as required, this being a difficulty with constant-speed induction motors. Railway work, and even tramway work, might provide other fields for this motor. The proposal to standardize railway electrification on the d.c. system is well known, but surely before this is finally settled some investigations and tests should be made with variable-speed a.c. induction motors without commutators. Such tests might prove that we are not yet ready for a standard system of railway electrification.

**Mr. F. Creedy** (*in reply*): With reference to Mr. Burr's remarks, the first point which he raises is with regard to the mechanical shock on changing speed in the case of a pole-changing machine where the speed is necessarily changed in a number of distinct steps. This is dealt with in the paper on page 319 in connection with Fig. 17. Two methods of regulating the rate of acceleration from one speed to the next are in use with squirrel-cage machines: (1) By resistance; used in the smaller sizes of the motor. (2) By means of an auto-transformer momentarily inserted; used in the larger sizes. Both these methods give absolutely perfect control of the rate of acceleration, and it is difficult to convey to anyone who has not seen the operation of such machines, how smoothly and easily they change from one speed to the next. Any mechanical shock would, of course, be most apparent in a belted machine, where it would either throw the belt off or at least throw it into violent oscillation. Belted machines, up to the largest sizes used, have been controlled in this way without trouble. As regards electrical shock or, in other words, current-rush, the use of resistances, although simple, gives rise to rather heavy currents on changing speed. With the auto-transformer method, however, one can obtain the results shown in Fig. 17 in which the current-rush on changing speed does not exceed twice full-load. A very simple form of drum-switch having 9 fingers is employed to make this change, and the small auto-transformer on a 30-second rating has very small dimensions. I cannot understand why Mr. Burr should think that to change the phases with the machine running would require very complicated and expensive switchgear, since the precise switchgear required is illustrated in the paper. It is sometimes possible to reduce the magnetizing current at the low speed so as to improve the power factor under these conditions, particularly in cases where the motor is never likely to be subjected to overload.

With reference to Mr. Isaacs's remarks, it is not as a rule very profitable to discuss questions of priority of this kind, but I may say the work mentioned herein has occupied a large number of years and was probably started quite as early as any other investigations on the subject. I note his point that power factor must be kept high if there is a power factor clause in the tariff. This, of course, is quite true, but what I contend is that such a clause is a mistake. Supply engineers should, in their own interests, insert a clause limiting the amount of magnetizing current to be taken by the consumer, rather than limiting his power factor. It is not fair to the consumer to penalize 1 kVA at 0·1 power factor more than 50 kVA at 0·8 power factor. Mr. Isaacs asks whether it is possible to use the cascade type of motor running as an induction motor at full load and full speed, and as a synchronous motor at unity power factor at the reduced speed. This is perfectly possible, and it so happens that only a few days before the meeting a machine of this type was ordered and is now under construction. I hope to be in a position, as soon as this machine has been tested, to publish further details, as this type is very interesting in many ways. It is now possible to obtain slip-ring control on this type of motor on as many as 4 to 6 speeds, and therefore the use of such a motor, in combination with a small commutating set to bridge the gaps, becomes a practical thing and will, it is believed, be developed as soon as business revives.

Replying to Mr. Jenkins, I may say that motors of this type are constantly being put forward to comply with the Mining Regulations, including Clause 132. As regards the speeds available, it is true, of course, that the multi-speed motor is used chiefly at low speeds and, except in small sizes, we do not as a rule offer even the speed of 1 500 r.p.m. For sizes up to about 25 h.p., a 1 500/1 000/750 r.p.m. combination is useful. Above that a higher speed than 1 000 r.p.m. is seldom required. It seems difficult to attach any meaning to Mr. Jenkins's statement that the induction motor is essentially and inherently a constant-speed machine, in view of the fact that induction motors are constantly being made in which the speed does vary. Undoubtedly such hydraulic gears as the Williams-Janney have their field of utility, as has every type of variable-speed apparatus, but it is not a practical substitute for a variable-speed motor of considerable size, even if we considered the cost alone. The curve given in Fig. 14 includes, on the one hand, the control gear and transformer for the operation of the multi-speed set, and, on the other hand, the standard induction motor and its standard starter.

With reference to Professor Bacon's remarks, it is very difficult for an individual to explain to others his methods of research. All one can say is that the best plan is to keep on studying the subject and its difficulties, and then all of a sudden, probably when one is not thinking of the subject at all, the right idea will come. Some of the drives for which these motors are used are machine tools, fans, compressors, pumps, haulage and winding engines, cement making machinery, calenders (rubber), grain elevators, wire-drawing and larger rolling mills, printing machinery, mine fans and compressors. Of course, only a.c. machines are applicable to the electrical propulsion of battleships, and, although this has not yet become a practical proposition in this country, it has been widely applied in the U.S.A.

As regards electrical traction, I did not say anything about it in the paper because a.c. traction in this country is out of fashion for the moment. A committee have decided that direct current is the thing for electric traction in England, but, without discussing whether this was or was not so at the period at which the committee sat, it is certain that the d.c. system has reached practically its full development and that further improvements are likely to be difficult and of a comparatively trivial nature. The a.c. system, on the other hand, is now in its infancy. There are many authorities who hold that even now it presents advantages over direct current. Again, without discussing this, it is certain that a revolutionary change such as the entire abolition of the commutator from the a.c. traction motor will be introduced in the not very distant future. More than one single-phase railway is already in operation, using induction-type motors. The introduction of carrier-current telephony has abolished the interference between the single-phase traction supply and the telephonic circuits, out of which such a bugbear has been made. Owing to the heavy taxation and financial difficulties of the railways, it seems likely that electrification will make slow progress for a few years, so that fortunately the opinions of the above committee will do little harm, and it will be possible to reconsider the matter in a few years' time on more progressive lines.

Referring to Mr. Haigh's remarks on 25-period plant, I may say that 25-period machines of moderate size, running at speeds of 750/500/375 r.p.m., can be supplied, and in larger sizes a greater number of speeds becomes available, though of course they are all rather low.

Coming to Mr. Howell's remarks, I would refer back to my reply to Mr. Isaacs. I think that the solution of Mr. Howell's problem is a small commutating set connected across the slip-rings of the main induction machine, in order to permit it to drop in speed so that the flywheel may give up its energy. This has not yet been put forward in any actual installation, but I have made several studies of plants for rolling-mill work in which as many as four distinct speeds are required to deal with different classes of work, and on each one it is possible to obtain 10 per cent slip regulation by putting resistance across the slip-rings, which are available on every one of the four speeds. Of course, the small commutating set will avoid the losses in this resistance when it has received commercial development.

Mr. Ashton is evidently an unrepentant advocate of d.c. work. I should be surprised to hear that I do not appreciate the qualities of modern commutator machines, as I believe I have done perhaps as much as anyone to develop modern a.c. commutator apparatus. It seems to me that one must discriminate between cases where commutator machinery is advantageous, and others where it is the reverse. I have just described how an a.c. apparatus involving a small commutating set connected across the slip-rings can be arranged to give the 10 per cent drop in speed at full load necessary to take advantage of the flywheel as a normal characteristic of the machine, and without the use of automatic switchgear. Mr. Ashton says that alternating current appeals chiefly to the distributing engineer, but I think that the local works are affected not only by the price of electrical energy, which must be materially less with alternating current, but also by the cost of motors, which is less for the induction type than for d.c. machines. The price of the variable-speed a.c. machine is higher at present than that of the corresponding d.c. machine, but comparing the two complete installations each containing a considerable number of motors, some variable-speed but the majority constant-speed, it will be found that the a.c. installation is far cheaper, since the higher cost of the variable-speed apparatus is completely offset by the lower cost of the constant-speed apparatus.

Referring to Mr. Allan's remarks, I have already dealt with the question of 25-period motors. Two-speed haulage motors for 3 000-volt circuits can be, and have been, built for many years past. There is no difficulty in building such machines up to 300 h.p., and many studies have been made of machines of such sizes. It is quite true that the driving of boiler fans forms a very satisfactory application for such machines. A convenient combination consists of a squirrel-cage machine arranged for speeds of 375/333/300 r.p.m. Such a machine involves practically the same initial outlay as a single-speed slip-ring machine in which the speed-range is obtained by continuously-rated resistances, owing to the great cost of the latter, and of course it shows a very great saving in running costs.

# DIRECTIONS FOR THE STUDY OF VULCANIZED FIBRE FOR ELECTRICAL PURPOSES.

[REPORT (REF. A/S4) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

## CONTENTS.

Page
Preface .. .. .. .. .. .. .. 964
I. Introduction .. .. .. .. .. 965
Raw Materials Employed in the Manufacture of Vulcanized Fibre .. .. .. 965
Zinc Chloride Solution ("Acid") .. .. 965
Colouring Matter .. .. .. .. 965
Methods of Manufacture .. .. .. 966
Chemical Composition of Vulcanized Fibre 966
Maturing of Vulcanized Fibre .. .. 966
Storing of Vulcanized Fibre .. .. 966

II. Definitions .. .. .. .. .. 967
(*a*) Definition of Vulcanized Fibre .. 967
(*b*) Definition of Vulcanized Fibre for Elec- 967
trical Purposes.. .. .. .. 967
(*c*) Terminology .. .. .. .. 967

III. Methods of Test—

1. Conditioning of Specimens for Test .. 967
2. Determination of Thickness .. .. 967
3. Determination of Density .. .. 967
4. Tensile Strength, Extension and Plastic Yield under Continuous Load .. 968
5. Compression Strength and Plastic Yield under Continuous Load .. .. 968
6. Shearing or Tearing Strength .. .. 969
7. Cohesion between Layers (Splitting Test) 970
8. Stiffness or Rigidity .. .. .. 972
9. Flexibility (Bending Test) .. .. 975
10. Electric Strength .. .. .. .. 975
11. Resistivity.. .. .. .. .. 977

Page
III. Methods of Test (*continued*)—

12. Surface Resistivity .. .. .. 977
13. Internal Resistance .. .. .. 978
14. Shrinking, Warping and Swelling .. 978
15. Machining Properties .. .. .. 979
16. Freedom from Chemical Reaction .. 979
17. Freedom from Conducting Particles and Pinholes.. .. .. .. .. .. 981
18. Effect of Oil .. .. .. .. 981
19. Absorption of Water .. .. .. 981
20. Slot Wedge Test .. .. .. .. 981
21. Freedom from Conducting Particles (for Material in Rolls only) .. .. 981

## PREFACE.

Vulcanized Fibre and Leatheroid are used in considerable quantities by electrical manufacturers, but the requirements of the electrical industry represent but a small percentage of the total output of vulcanized fibre. As most of the vulcanized fibre is made, therefore, for other than electrical purposes, much of it is unsuitable, or suitable only for particular applications.

The attention of the Association was drawn to the need that exists for studying the properties of vulcanized fibre so as to discriminate between materials suitable for the requirements of the electrical industry and those which are unsuitable.

A large amount of experimental work has been carried out directed to the development of methods of test, and will form the subject of a detailed report to follow.

Meanwhile the Association recommends the methods described herein for the full study of this class of material, but it is realized that some of the tests are too elaborate for use as acceptance tests for the purchase of vulcanized fibre.

The British Engineering Standards Association has been asked to issue a Purchasing Specification for vulcanized fibre in which reference will be made to such of the tests described herein as are suitable for the purpose.

The Director of the E.R.A. will value comments and criticisms from those who have occasion to use any of the tests given in this specification.

## I. INTRODUCTION.

The term "fibre" has in the past been used to cover a very large range of materials which are similarly manufactured, but vary appreciably in quality. These materials are sold under a wide range of different trade names, as for instance :—

Hard Fibre.
Vulcanized Fibre.
Leatheroid.
Fiberoid.
Fish Paper.
Peerless Insulation.
Delaware Insulation.
Diamond Insulation.
Whalebone Fibre.
Vegetable Fibre.
Superseasoned Fibre.
Egyptian Fibre.
Red Fibre.
Conite.
Horn Fibre.

Two distinct materials are on the market under the name of horn fibre, one of which is a comparatively high quality vulcanized fibre. The other is a special product which should correctly be described as Felted Jute Board, as it is not made by a process entailing the use of chemicals.

In view of the fact that similar raw materials are used and that the processes of manufacture are identical, it has been decided to regard all the materials mentioned above as coming within the scope of the definition of vulcanized fibre given in Section II.

It is recognized that vulcanized fibre is obtainable in the following grades :—

*Grade A.*—Best quality vulcanized fibre free from mineral salts, made from selected raw materials having good mechanical and electrical characteristics. This grade includes the following :—

Natural grey (unbleached).
Best quality red and black.
Leatheroid.

*Grade B.*—Ordinary quality vulcanized fibre having moderately good mechanical characteristics. This grade includes the bulk of the coloured vulcanized fibre.

*Grade C.*—A third grade of vulcanized fibre specially produced for making trunks, roving cans, containers, etc., is obtainable, but it is considered that this material is entirely unsuitable for electrical purposes.

It has been decided that the scope of this Specification shall be limited to Grade A vulcanized fibre only.

### RAW MATERIALS EMPLOYED IN THE MANUFACTURE OF VULCANIZED FIBRE.

*Paper.*

The paper used in manufacturing high-quality vulcanized fibre is generally made from well-worn white cotton rags, and great care has to be taken to ensure that no impurities get into the beaters with the rags. Vulcanized fibre made from paper produced from new cotton does not show the same high quality as that made from worn rags. This is explained in two ways :—

First, that the frequent washings to which old rags have been subjected have removed practically the whole of the greasy hydrocarbons which are naturally associated with a fresh cotton fibre, and

Secondly, that the characteristic twists in the cotton fibre to which Sea Island, Egyptian, American and other varieties of cotton generally used for spinning owe their superiority are accentuated by having been spun, woven and frequently washed in that condition before being beaten for the manufacture of paper.

### ZINC CHLORIDE SOLUTION ("ACID").

The solution which is employed to dissolve the surface of the paper before it is made into vulcanized fibre is, in general, zinc chloride, although other solutions, including cupra-ammonium nitrate, calcium chloride, thiocyanate solution, etc., have been suggested. The zinc chloride employed must be free from impurities and kept at a temperature of 40° C., with a specific gravity of 1·8, although these values necessarily require slight adjustment depending upon the quality of the paper being used. Vulcanized fibre makers refer to this solution as "acid," and hence the commonly held idea that vulcanized fibre is liable to contain acid, whereas in point of fact it is usually very slightly alkaline.

### COLOURING MATTER.

In the manufacture of vulcanized fibre for electrical purposes, colouring matter should as far as possible be avoided, and for this reason it is generally held that the natural-coloured vulcanized fibre is the best for electrical purposes.

Certain grades of good black vulcanized fibre are nevertheless obtainable, and in this case no dyes are used to colour the paper during its manufacture, but the "rags" used are Italian linings and black cotton stockings which have been well worn and many times washed. Attempts to make black vulcanized fibre using black bone ash or indigo dyes have been found to deteriorate slightly the properties of the vulcanized fibre.

Red vulcanized fibre is coloured by the use of iron oxide or red aniline dyes. It is thought that both of these dyes are liable to deteriorate the vulcanized fibre slightly. The presence of the latter dye can usually be suspected in vulcanized fibre sheets which have a particularly bright red (red-crimson) appearance.

In some materials, as for instance leatheroid, the grey colour is obtained by mixing pulps made from white cotton rags with about 10 per cent of black cotton pulp made from stockings, etc. The dyes do not run to form grey, but the presence of the black fibres gives the material a grey appearance.

### Methods of Manufacture.

*Boards.*

In manufacturing vulcanized fibre, paper is passed through a bath containing the zinc chloride solution, and maintained at approximately 40° C. at 1·8 specific gravity. From the bath the paper passes over a large heated drum on which it is wound until the required thickness is obtained. The cylinder of treated paper is then slit so that it falls off the drum into a flat sheet. In this state the sheet is extremely pliable and soft, and liable to be easily damaged.

The sheets are then passed through a series of tanks or " tubs " in which they are immersed in solutions of zinc chloride diminishing in strength until finally the vulcanized fibre is immersed in pure water. This washing process may occupy anything from six days for the thinnest sheets made on continuous machines to twelve months on sheets over one inch in thickness. The reason for such a lengthy washing process is that there is a great tendency for the zinc chloride to hydrolize and deposit zinc hydroxide and zinc oxychloride in the vulcanized fibre. In this manner, serious blisters may be formed in the sheets which have to be relieved by pricking. Experience has shown that the only way to avoid these blisters is to arrange for the vulcanized fibre to pass very gradually through the varying strengths of zinc chloride solution.

After removal from the tanks, the sheets are allowed to dry at a temperature from 40° C. to 60° C. This drying process must necessarily be one of several weeks, and during that period the vulcanized fibre sheet should shrink approximately 10 per cent. The longer this process is carried out the more complete does the maturing, and consequently the shrinkage, of the vulcanized fibre become. When thoroughly dried and shrunk the board is frequently calendered, pressed, trimmed, and is then ready for sale.

*Thin Material in Rolls.*

Thin material in rolls, as for instance, thin vulcanized fibre, leatheroid, etc., is manufactured by a continuous process, involving the use of very large and expensive machinery. In this process the continuous roll of material, after being rolled into a sheet of required thickness by superimposing paper (treated with zinc chloride) fed from a number of feed rolls, is passed first through a series of vats, in which the washing process is completed in approximately six days, and then through a rapid drying oven. The material is in a continuous length from the time it is pressed together until it is taken out dry from the machine.

Certain thin materials are on the market as " hand-made." This implies that the process employed is much the same as for sheets and the " continuous process " machine described above has not been used. " Hand-made " thin sheets can be allowed greater washing and drying periods, and are, therefore, generally superior material.

*Rods.*

Rods are made by turning up square bars sawn from board.

*Tubes.*

A tube is made by winding cotton paper treated with zinc chloride on to a mandrel until the required thickness is obtained. The tube is afterwards removed from the mandrel, subjected to the washing process and dried.

It is due to this difference in manufacture of tubes and rods that a tube should, in general, be specified and used when possible for bushes, etc., as a rod possesses a natural tendency to split along the laminæ of the board from which is was cut.

### Chemical Composition of Vulcanized Fibre.

The chemical composition of vulcanized fibre is as follows :—

| | | |
|---|---|---|
| Amyloid (converted cellulose) | 93 % | to 85 % |
| Moisture .. .. .. | 6·4 % | to 12 % |
| Insoluble salts of Sn, Si, Al, Fe, Zn, Ca, Mg .. .. | 0·6 % | to 3 % |
| | 100 % | 100 % |

### Maturing of Vulcanized Fibre.

From a large number of tests which have been conducted by the Association in making the present study of vulcanized fibre, the importance of careful and prolonged maturing has been repeatedly emphasized. Due to the war conditions, which resulted in greatly depleted stocks, a large amount of vulcanized fibre has, during the past few years, been released from manufacturers' warehouses before it had been subjected to the long period of maturing which was common in pre-war days. This, amongst other points, has been largely responsible for a considerable amount of poor quality vulcanized fibre that has been put on the market during the last few years since 1918.

It is extremely difficult to measure the exact effect of maturing, but an investigation of this nature is being put in hand.

### Storing of Vulcanized Fibre.

A number of tests which have recently been carried out indicate that careful storage of vulcanized fibre is of the utmost importance if consistent good results are to be obtained. A comparatively good grade of vulcanized fibre can be more or less ruined by being stored in a damp atmosphere, or even in an atmosphere of which the conditions of temperature and humidity are frequently changed. It is of the utmost importance that vulcanized fibre stocks should be kept in a carefully controlled atmosphere with the temperature slightly above that of ordinary room temperature and the relative humidity 60 to 65 per cent. Boards should always be stored standing on their edges, and be suitably separated so that the air has as much free access to them as possible.

## II. DEFINITIONS.

(*a*) *Definition of Vulcanized Fibre.*

The term " Vulcanized Fibre " denotes all materials, including Leatheroid, made of superimposed layers of paper chemically treated (usually with zinc chloride), so that the laminæ are virtually destroyed, and a homogeneous mass of converted cellulose is produced.

(*b*) *Definition of Vulcanized Fibre for Electrical Purposes.*

For purposes of this Specification one grade of Vulcanized Fibre only is recognized as follows :—

Best quality vulcanized fibre, free from mineral salts, made from selected raw materials and having good mechanical and electrical characteristics.

NOTE.—It is recognized that other grades of vulcanized fibre are obtainable, but these are considered to be outside the scope of this Specification.

(*c*) *Terminology.*

(i) The term " Longitudinal " denotes the direction parallel to that in which the material travelled during manufacture.
(ii) The term " Transverse " denotes the direction at right angles to that described in (i) above.
(iii) The term " Perpendicular " denotes the direction normal to the surface of the material.

NOTE.—When the material is built up of superimposed layers having the " grain " at right angles, there is no definite longitudinal or transverse direction.

## III. METHODS OF TEST.

### 1. CONDITIONING OF SPECIMENS FOR TEST.

Before the tests specified in Clauses 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 19, and 20 are carried out the specimens shall be dried at a temperature from 75° C. to 80° C. for 18 to 24 hours, and the test shall be conducted as soon as the temperature of the specimen has fallen to 20° C. (± 5° C.).

The conditioning of the specimens for the electric strength test, Clause 10, shall be carried out as specified in Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials.*

### 2. DETERMINATION OF THICKNESS.

The specimen shall be conditioned in accordance with Clause 1 before the thickness is measured.

(*a*) *Boards.*

Measurements of thickness shall be made by means of a suitable micrometer at ten points equally spaced around the sides of the board. The maximum, minimum, and mean values of thickness shall be stated.

(*b*) *Rods and Tubes.*

The diameter of the rod, and in the case of a tube the internal and external diameters of the tube, shall be measured at each end. Two measurements shall be made on diameters at right angles in each case by means of a suitable micrometer.

The maximum, minimum and mean values of the diameter of the rod, and the diameters of the tube shall be stated.

### 3. DETERMINATION OF DENSITY.

The specimen shall be conditioned in accordance with Clause 1 before the density is determined.

(*a*) *Boards.*

A specimen 1½ inches square shall be used to determine the density of the material.

The area of the specimen shall be computed from the mean of ten measurements of the length and the width respectively at points equally spaced along each of two edges at right angles. The thickness shall be determined by making ten measurements with a suitable micrometer equally spaced around the sides of the board, and the mean value shall be taken in computing the volume of the specimen.

The usual precautions shall be observed in weighing the specimen, and the weight shall be taken to the nearest milligramme in each case.

The density shall be expressed in terms of weight in grammes per $cm^3$.

NOTE.—When carrying out acceptance tests on bulk consignments it will frequently be found desirable to weigh and measure the entire boards as received. This test affords a rapid means of checking the density of the vulcanized fibre without cutting the board, and should be conducted before cutting specimens for other tests.

(*b*) *Rods and Tubes.*

The dimensions of a rod or tube 1½ inches long shall be determined by means of a micrometer or other suitable method.

The diameter of the rod, and in the case of a tube the internal and external diameters of the tube, shall be measured at each end and at the centre. Two measurements shall be made on diameters at right angles in each case. The length of the specimen shall be determined by making four measurements equally spaced around the circumference of the ends, and in the case of a rod a fifth measurement of length shall be made on the axis of the rod. The volume of the specimen shall be computed from the mean value in each case.

---

* See *Journal I.E.E.*, 1922, vol. 60, p 794.

The usual precautions shall be observed in weighing the specimen, and the weight shall be taken to the nearest milligramme in each case.

The density shall be expressed in terms of weight in grammes per $cm^3$.

### 4. Tensile Strength, Extension and Plastic Yield under Continuous Load.

The specimen shall be conditioned in accordance with Clause 1 before the tests for tensile strength and extension are carried out.

(*a*) *Boards.*

The form and dimensions of the specimen for testing a board shall be as shown in Fig. 1. The thickness of the test bar shall be the thickness of the material.

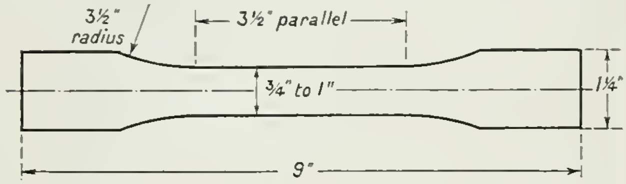


Fig. 1.—Specimen for Tensile Strength and Extension Tests on Boards.

(i) The specimen shall be tested longitudinally and transversely to ascertain the ultimate tensile strength and the extension on a 3-inch gauge length.

The load shall be increased steadily at such a rate that the specimen breaks in approximately two minutes from the time of the application of the load.

The ultimate tensile strength shall be expressed in lb. per sq. in. The extension shall be expressed as a percentage on the original gauge length.

(ii) The specimen shall be tested to ascertain the extension on a 3-inch gauge length when subjected continuously to a load of a value equal to one-third of the breaking load, determined by test (i) above. The load shall be maintained until the increase of strain ceases.

(*b*) *Rods.*

The form and dimensions of the specimen for testing a rod shall be as shown in Fig. 2.

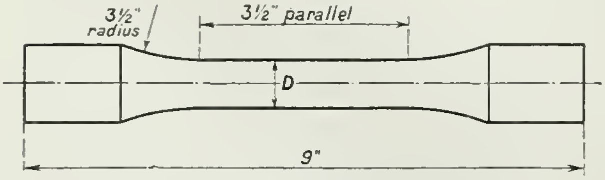


Fig. 2.—Specimen for Tensile Strength and Extension Tests on Rods.

The reduced diameter D shall be 75 per cent of the full diameter of the rod.

Specimens shall be tested as specified in (*a*) (i) and (ii) above.

(*c*) *Tubes.*

The dimensions of the tube for test shall be 9 inches long, 1 inch internal diameter, and 1½ inches external diameter.

Specimens shall be tested as specified in (*a*) (i) and (ii) above.

A suitable form of grip for holding the tube in the testing machine is shown in Fig. 3.

### 5. Compression Strength and Plastic Yield under Continuous Load.

(*a*) *Boards.*

(i) The specimen shall be conditioned in accordance with Clause 1 before the compression strength test is carried out.

The dimensions of the specimen for test shall be 1-inch cube, the specimen being built up with several layers of the material when necessary. The layers of the material shall be bedded together by the application of an initial load of 300 lb. per sq. in., and the first measurement of the length of the specimen shall be taken under this load, which shall be included in the load registered in each case.

A series of tests shall then be carried out at a temperature from 15° C. to 25° C. by the application of increasing loads of 1 500 lb. per sq. in., each of which shall be maintained for one minute, and the yield of the specimen shall be measured at the end of each period. The tests shall be continued until the specimen has yielded 10 per cent of its original length, when measured as stated above, or the load has reached to about 6 tons per sq. in.

(ii) A specimen similar to that described in (i) above shall be heated in air at a temperature from 90° C. to 95° C. for 24 hours, and then tested at a temperature from 90° C. to 95° C. The specimen shall be bedded, the loads applied, the yields measured, and the test continued as specified in (i) above.

(iii) A specimen similar to that described in (i) above shall be immersed in transformer oil, complying with British Standard Specification No. 148 for light-grade oil, at a temperature from 90° C. to 95° C. for 24 hours, and then tested at a temperature from 90° C. to 95° C. The specimen shall be bedded, the loads applied, the yields measured, and the test continued as specified in (i) above.

(iv) A specimen similar to that described in (i) above shall be heated in air at a temperature from 90° C. to 95° C. for 24 hours and then subjected continuously, at a temperature from 90° C. to 95° C. to a load of a value equal to one-third of the maximum load applied in the test specified in (ii) above. The load shall be maintained until the increase of strain ceases. The yield shall be measured at intervals, and a curve plotted showing the relationship between the yield and the time of application of the load.

(v) When the thickness of the material is ⅜ inch or above, it shall be also tested at a temperature from

15° C. to 25° C. for compression strength in the longitudinal direction.

The specimen shall be conditioned in accordance with Clause 1 before the compression test is carried out.

The dimensions of the specimen shall be 2 inches in the longitudinal direction of the sheet, and 1 inch in the transverse direction, the load being applied on the 2-inch edges of the specimen.

The load shall be increased gradually at the rate of 1 500 lb. per sq. in. per minute until the specimen fails. The load at which failure occurs and the duration of the test shall be stated.

(vi) A specimen similar to that described in (v) above shall be heated in air at a temperature from 90° C. to 95° C. for 24 hours, and then tested at a temperature from 90° C. to 95° C. The load shall be applied and the test continued as specified in (v) above.

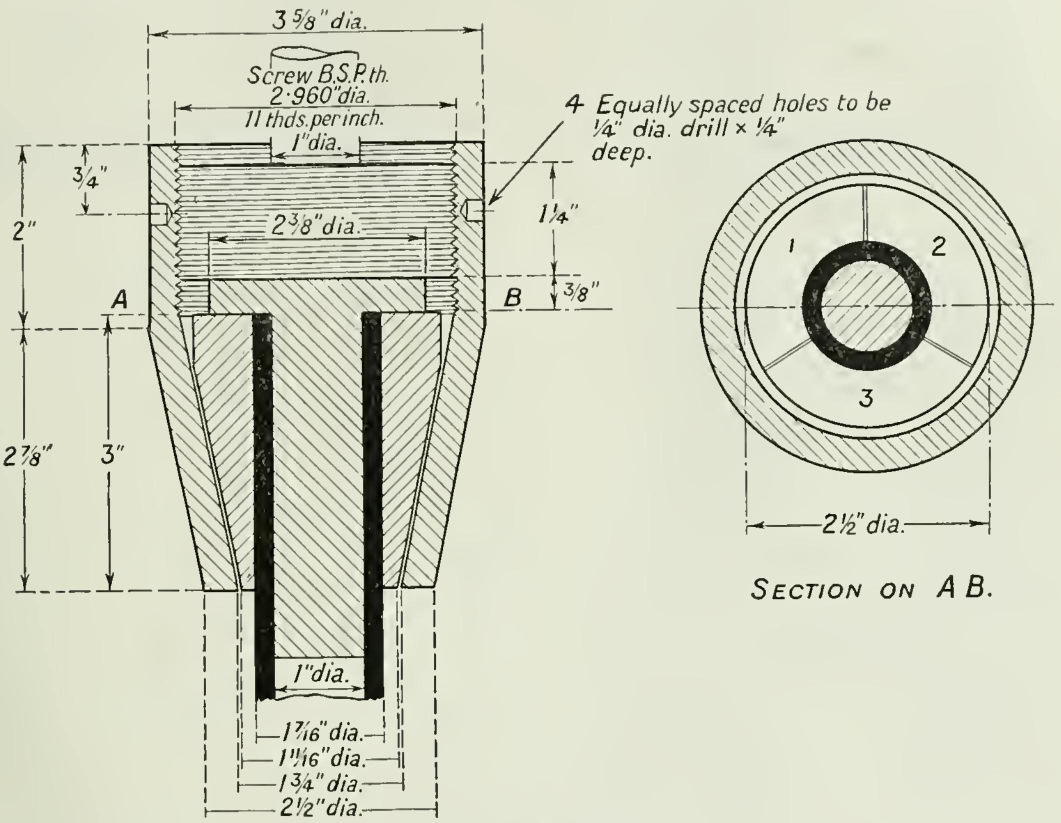


FIG. 3.—Form of Grip for holding Tube in Testing Machine for Tensile Strength and Extension Tests.

(*b*) *Rods.*

The form of the specimen for test shall be a cylinder, the length of which shall be equal to the diameter of the rod. The end faces of the specimen shall be truly plane, square and parallel.

An initial load of 300 lb. per sq. in. shall be applied, and the first measurement of the length of the specimen shall be taken under this load, which shall be included in the load registered in each case.

Specimens shall be tested as specified in (*a*) (i), (ii), (iii) and (iv) above.

(*c*) *Tubes.*

The form of the specimen for test shall be a tube the thickness of wall being not less than $\frac{1}{8}$ inch, and the length of which shall be equal to the external diameter of the tube. The end faces of the specimen shall be truly plane, square and parallel.

An initial load of 300 lb. per sq. in., computed on the cross-sectional area of the material, shall be applied, and the first measurement of the length of the specimen shall be taken under this load, which shall be included in the load registered in each case.

Specimens shall be tested as specified in (*a*) (i), (ii), (iii) and (iv) above.

### 6. SHEARING OR TEARING STRENGTH.

The specimens shall be conditioned in accordance with Clause 1 before the test for shearing or tearing strength is carried out.

(*a*) *Boards.*

(i) *Shearing Strength.*

Materials above 1/32 inch thick up to and including $\frac{1}{8}$ inch thick shall be tested to ascertain the force required to punch a hole $\frac{1}{2}$ inch in diameter.

The load shall be applied steadily, and shall be increased at a rate of approximately 100 lb. per minute for each 1/32 inch thickness of the specimen.

The clearance between the punch and the die shall be negligible as obtained by trimming the punch with the die.

The pressure required to punch the hole shall be expressed in lb. per sq. in.*

Materials above $\frac{1}{8}$ inch thick shall be tested as follows :—

A specimen, the dimensions of which shall be 5 inches long and $2\frac{1}{2}$ inches wide, shall be clamped in a shear testing jig so that both ends of the specimen are sheared off simultaneously. The pressure required to produce shear shall be computed on the total area of the sections sheared, and shall be expressed in lb. per sq. in.

The load required to tear the specimen shall be expressed in lb.

(*b*) *Rods.*

A specimen 5 inches long and the full diameter of the rod shall be clamped in a shear testing machine so that both ends of the specimen are sheared off simultaneously. The pressure required to produce shear shall be computed on the total area of the sections sheared, and shall be expressed in lb. per sq. in.

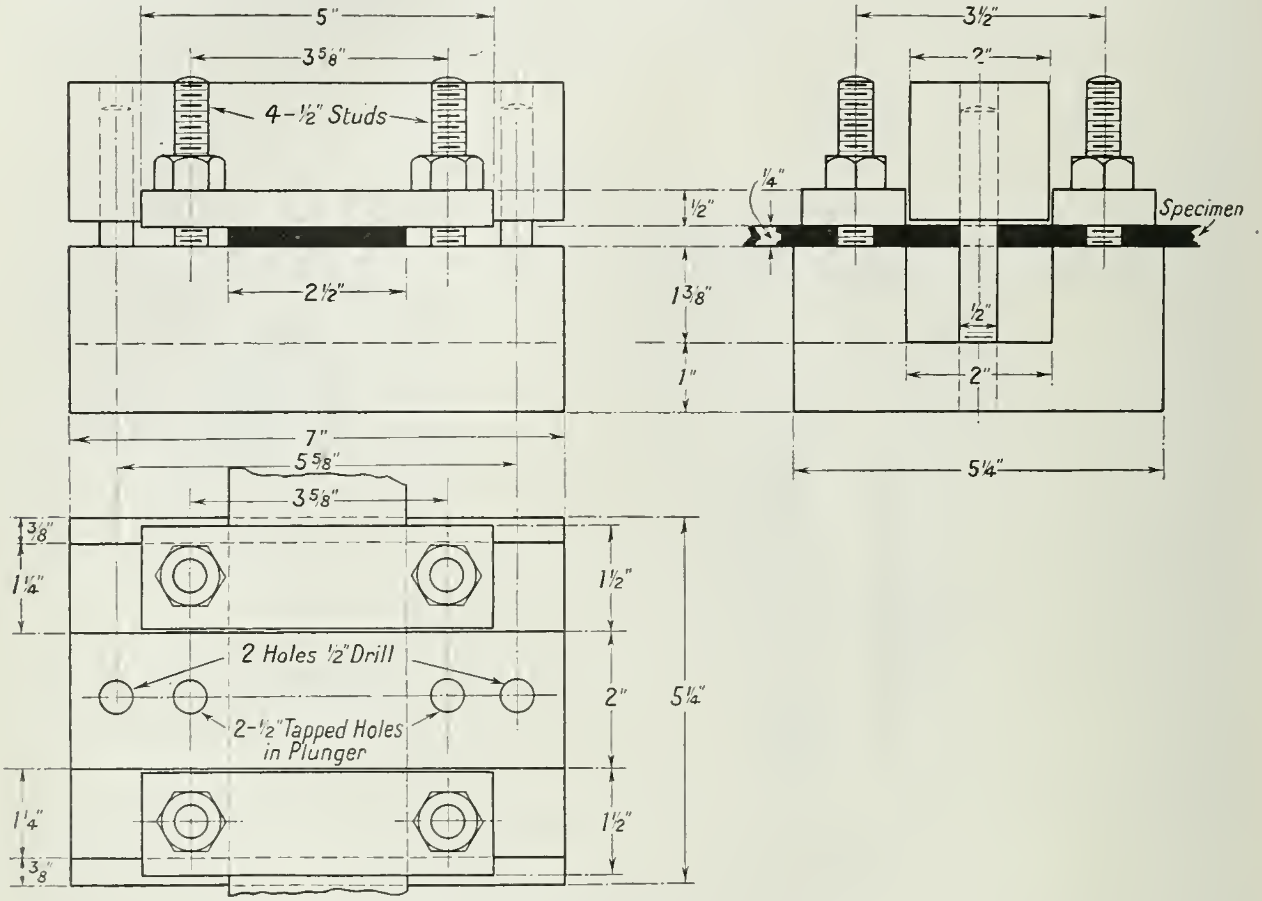


FIG. 4.—Form of Jig for the Shear Test on Boards.

A suitable form of jig for the shear test is shown in Fig. 4.

(ii) *Tearing Strength.*

Materials up to and including 1/32 inch thick shall be tested for tearing strength as follows :—

The form and dimensions of the specimen for test shall be 6 inches square.

The tearing strength shall be the load required to tear the specimen commencing from a hole 3/32 inch diameter and punched out of the specimen. The position of the hole and the application of the load shall be as shown in Fig. 5.

Three longitudinal and three transverse tear tests shall be carried out on each material under test.

7. COHESION BETWEEN LAYERS (SPLITTING TEST).

The specimens shall be conditioned in accordance with Clause 1 before the tests for cohesion between layers are carried out.

(*a*) *Boards.*

Cohesion between layers shall be tested by the following method :—

(i) The dimensions of the specimen shall be as follows :—

Width = 1 inch.
Thickness = Thickness of the material.
Length = Four times the thickness plus $\frac{1}{2}$ inch.

The specimen shall be supported on V supports spaced apart at a distance equal to four times the

---

* In a future edition of this Specification it is probable that the shear stress will be substituted for the pressure required to punch the hole.

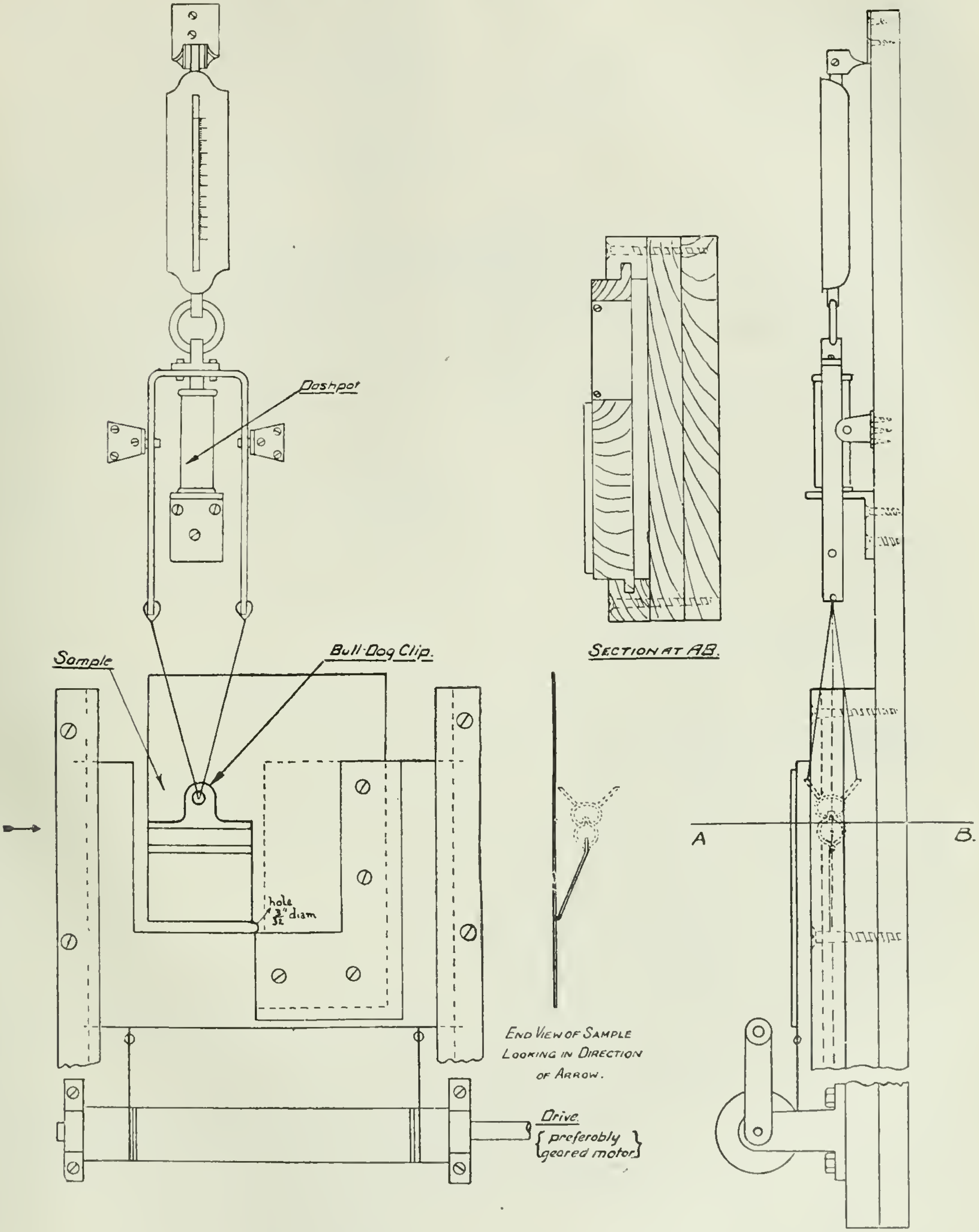

Dashpot
Sample
Bull-Dog Clip.
hole 3/32" diam
Section at AB.
A
B.
End View of Sample Looking in Direction of Arrow.
Drive.
{preferably geared motor}

Fig. 5.—Apparatus for Measuring the Tearing Strength.

thickness of the material under test. A load shall be applied centrally on the specimen and increased until failure occurs. The load required to cause failure and the nature of the fracture shall be stated.

(ii) A specimen 2 inches square shall be tested to ascertain whether it is possible to split the material parallel to the laminations when a split has been started at one corner by the insertion of a knife.

(*b*) *Rods.*

The test shall be as outlined for sheets, except that the rod shall be of a length equal to three times its diameter plus $\frac{1}{2}$ inch, and shall be supported for test on **V** blocks spaced apart to a distance equal to three times the diameter of the rod. The rod shall lie so that the load is applied perpendicularly to its laminæ.

(*c*) *Tubes.*

A specimen of tube shall be cut of length equal to the external diameter, and shall be subjected to a crushing load perpendicular to the axis of the tube. The load required to cause failure and the nature of the fracture shall be stated.

### 8. Stiffness or Rigidity.

The specimen shall be conditioned in accordance with Clause 1 before the test for stiffness or rigidity is carried out.

(*a*) *Boards.*

Materials shall be tested for stiffness or rigidity by the cantilever method as follows :—

The form and arrangement of the test shall be in accordance with Figs. 6 and 7.

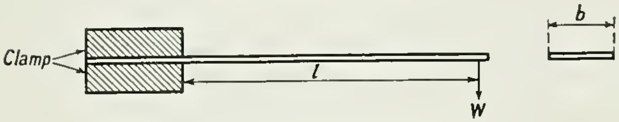


Fig. 6.—Form of Test for Stiffness or Rigidity.

The specimen shall be firmly fixed in clamps and the stirrup and scale pan placed in position as shown in Fig. 7. A measurement shall be made of the unsupported end below datum as follows :—

An inside micrometer shall be clamped above the stirrup. The electric circuit shall be as shown in Fig. 7. The micrometer screw shall be turned until the circuit is closed (as indicated by the voltmeter) and the micrometer reading shall then be taken.

Small equal increments of load shall be applied and the corresponding increments in deflection measured immediately. Each increment of load shall be applied as soon as the deflection for the previous load increment has been read. Readings shall only be taken for the range during which the increment of load is proportional to the increment of deflection.

The dimensions of the specimen shall be as follows :—

For specimens not exceeding 1/16 inch thick :—

Cantilever length = 2 inches.
Breadth = $\frac{3}{4}$ inch.

The increment of deflection shall not exceed 0·010 inch.

For specimens exceeding 1/16 inch thick the cantilever length shall be from 3 inches to 9 inches according to the stiffness of the material.

The breadth of the specimen shall be one-fifth of the cantilever length.

The increment of deflection shall not exceed 0·015 inch.

Young's Modulus, *E*, shall be computed from the following formula :—

$$E = \frac{4WL^3}{BD^3Y}$$

where $W$ = average increment of load lb.,
$L$ = cantilever length, inches,
$B$ = breadth, inches,
$D$ = thickness of specimen, inches,
$Y$ = average increment of deflection, inches.

When the final increment of deflection has been measured as described above the load shall not be removed. The increment of deflection shall be re-measured after 1 minute, 10 minutes, 1 hour and 18 hours respectively.

After the 18-hour test has been completed, tests at loads of 0·66 and 1·5 times respectively the value of the load employed in the 18-hour test shall be applied to the specimen, and the increments of deflection shall be re-measured as before in the prolonged test.

Note.—A suitable form of knife-edge balance for use in the cantilever test is shown in Fig. 8.

(*b*) *Rods.*

Rods shall be tested for stiffness or rigidity by the cantilever method as follows :—

The form and arrangement of the test shall be similar to that indicated in Fig. 7.

The rod shall be straight and of uniform diameter. Tests shall be carried out in directions parallel to and perpendicular to the laminæ respectively.

The length of the cantilever shall be as follows :—

| Diameter of Rod, inch | Cantilever Length, inches |
|---|---|
| $\frac{1}{4}$ | 4 |
| $\frac{1}{2}$ | 6 |
| $\frac{5}{8}$ | 8 |
| $\frac{3}{4}$ | 12 |

The specimen shall be firmly clamped upon a length not less than four times its diameter, and the stirrup and scale pan placed in position, as in the test for boards.

The dimensions of the clamp for holding the specimen shall be as shown in Fig. 9, and the two halves shall be separated by sheets of metal whose thickness is approximately equal to $\frac{1}{8}$ of the diameter of the specimen.

$D$ = diameter of specimen, inches.
$b$ = not less than $2D$ (and not less than 1 inch for small specimens).
$h$ = $2D$ (approximately).
$l$ = not less than $4D$.

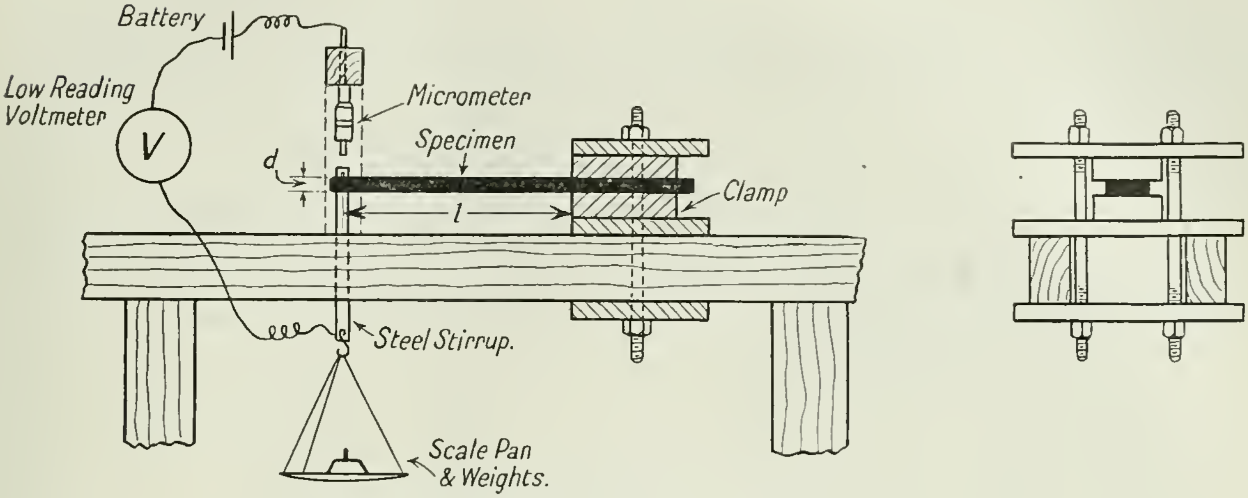


FIG. 7.—Arrangement of Cantilever Test for Boards.

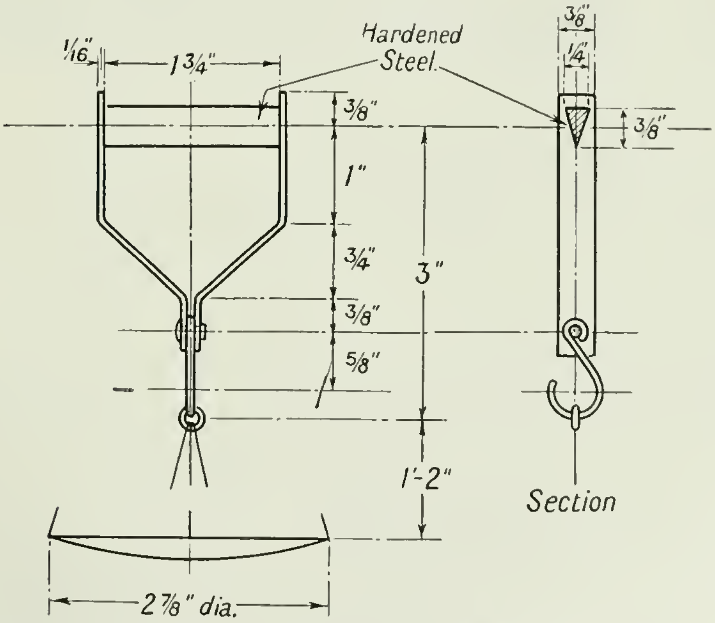


FIG. 8.—Form of Knife-edge Balance for Cantilever Test.

Note.—A suitable form of knife-edge balance for use in the cantilever test is shown in Fig. 8.

A measurement shall be made of the unsupported end below datum as follows :—

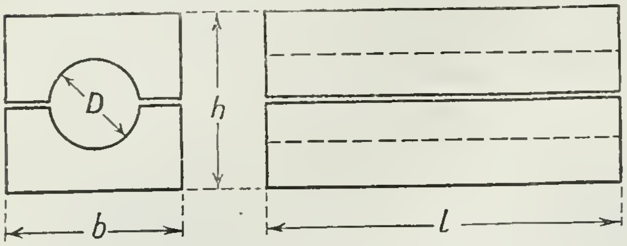


Fig. 9.—Form of Clamp for holding Rod in Cantilever Test.

An inside micrometer shall be clamped above the knife-edge piece. The electric circuit shall be as shown in Fig. 7. The micrometer screw shall be turned until the circuit is closed (as indicated by the voltmeter), and the micrometer reading shall then be taken.

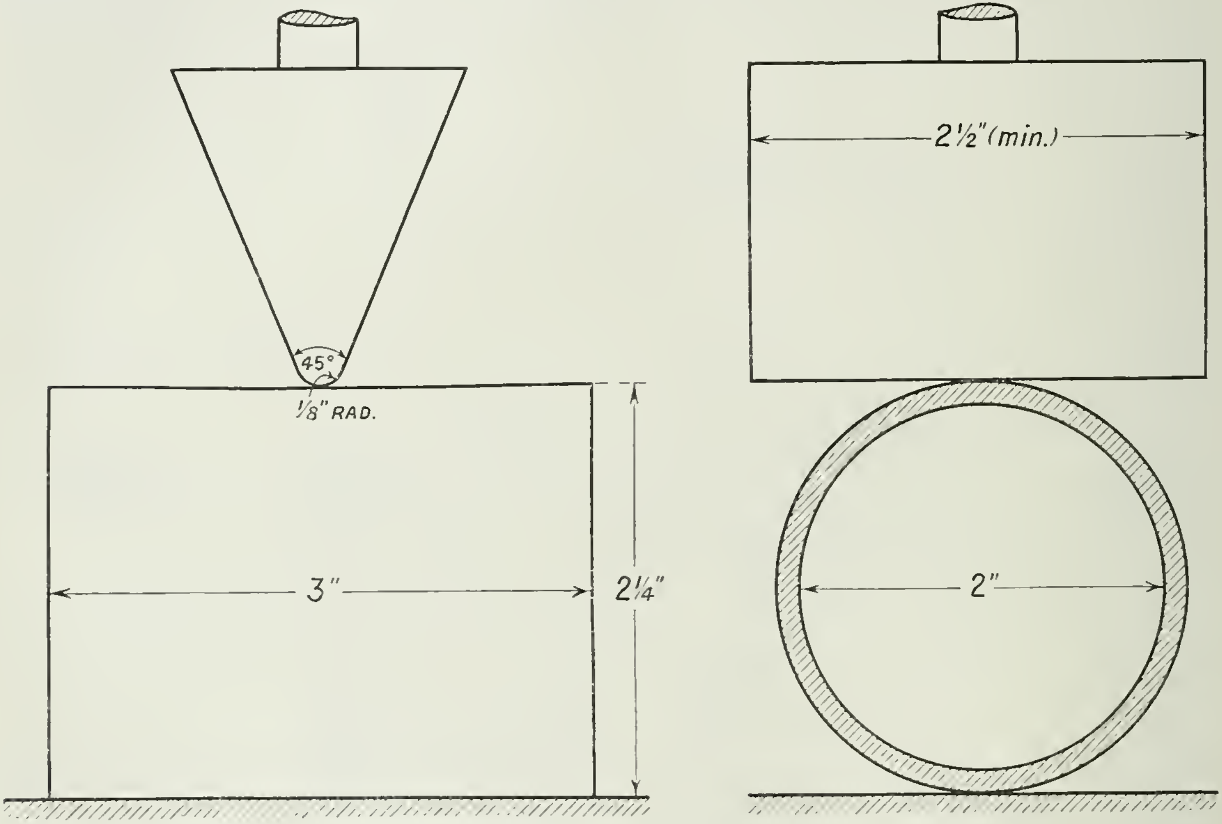


Fig. 10.—Arrangement of Stiffness Test for Tubes.

Small equal increments of load shall be applied, and the corresponding increments in deflection measured immediately. Each increment of load shall be applied without delay as soon as the deflection for the previous load increment has been read. Readings shall only be taken for the range during which the increment of load is proportional to the increment of deflection.

Young's Modulus, $E$, shall be computed from the following formula :—

$$E = \frac{64WL^3}{3\pi D^4 Y}$$

where $W$ = average increment of load, lb.,
$L$ = cantilever length, inches,
$D$ = diameter of specimen, inches,
$Y$ = average increment of deflection, inches.

When the final increment of deflection has been measured as described above the load shall not be removed. The increment of deflection shall be remeasured after 1 minute, 10 minutes, 1 hour and 18 hours respectively.

After the 18-hour test has been completed, tests at loads of 0·66 and 1·5 times respectively the value of the load employed in the 18-hour test shall be applied to the specimen, and the increments of deflection shall be re-measured as before in the prolonged test.

### (c) *Tubes.*

A tube 3 inches long, 2 inches internal diameter, and $2\frac{1}{4}$ inches external diameter shall be set up in a compression testing machine as shown in Fig. 10.

The load shall be applied to the top of the specimen, and midway between the ends, by means of a wedge-shaped plunger not less than $2\frac{1}{2}$ inches wide, the bottom edge of which is rounded to a radius of $\frac{1}{8}$ inch. The angle of the wedge shall be approximately 45°, and its axis shall be at right angles to the axis of the tube, as shown in Fig. 10. The load shall be increased by steps, and sufficient readings of the load and travel of the plunger taken up to the load at which failure occurs to enable a stress-strain curve to be plotted.

9. Flexibility (Bending Test) (for Material up to $\frac{1}{8}$ inch thick).

Flexibility tests shall be carried out on sheet material as follows :—

(*a*) *After Conditioning* (*before Baking*).

The specimen shall be conditioned in accordance with Clause 1 before the flexibility test is carried out.

A specimen of every thickness up to and including $\frac{1}{8}$ inch shall be bent longitudinally and transversely through an angle of 180°, and the effect on the specimen shall be stated. The radius of the corner round which the specimen is bent shall be in accordance with the appropriate value given in Table 1.

(*b*) *After Baking.*

A specimen of every thickness up to and including $\frac{1}{8}$ inch shall be heated for 48 hours at a temperature from 105° C. to 110° C. and allowed to cool to 20° C. (± 5° C.). It shall then be bent longitudinally and transversely through an angle of 180°, and the effect on the specimen shall be stated. The radius of the corner round which the specimen is bent shall be in accordance with the appropriate value given in Table 2.

Table 1.

*Radii of Corners to be used in Flexibility Test after Conditioning (before Baking).*

| Limits of Thickness of Specimen, inch | Radius of Corner, inch |
|---|---|
| Up to 1/32 .. .. .. | 1/16 |
| Above 1/32 up to 1/16 .. .. | $\frac{1}{8}$ |
| Above 1/16 up to $\frac{1}{8}$ .. .. | $\frac{3}{4}$ |

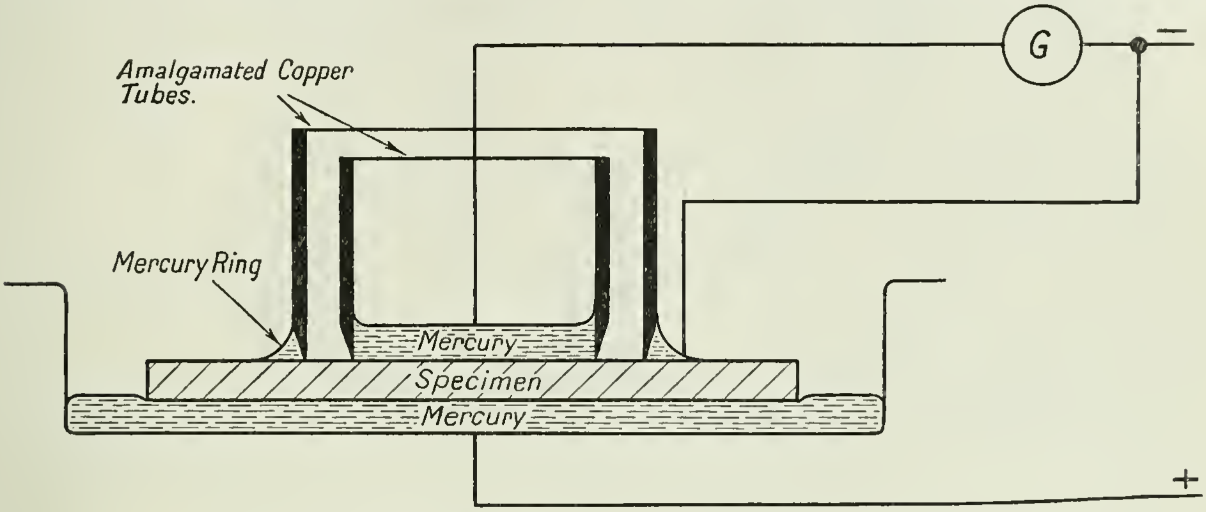


Fig. 11.—Diagrammatic Arrangement of Apparatus for Volume Resistivity Test.

(*c*) *After Heating in Oil.*

The specimen shall be heated in transformer oil, complying with British Standard Specification No. 148 for light-grade oil, for 48 hours at a temperature from 115° C. to 120° C., and shall then be bent longitudinally and transversely through an angle of 180°, and the effect on the specimen shall be stated. The radius of the corner round which the specimen is bent shall be in accordance with the appropriate value given in Table 3.

Table 2.

*Radii of Corners to be used in Flexibility Test after Baking.*

| Limits of Thickness of Specimen, inch | Radius of Corner, inch |
|---|---|
| Up to 1/32 .. .. .. | $\frac{3}{8}$ |
| Above 1/32 up to 1/16 .. .. | 1 |
| Above 1/16 up to $\frac{1}{8}$ .. .. | $2\frac{1}{2}$ |

Table 3.

*Radii of Corners to be used in Flexibility Test after Heating in Oil.*

| Limits of Thickness of Specimen, inch | Radius of Corner, inch |
|---|---|
| Up to 1/32 .. .. .. | $\frac{3}{4}$ |
| Above 1/32 up to 1/16 .. .. | $1\frac{3}{4}$ |
| Above 1/16 up to $\frac{1}{8}$ .. .. | $3\frac{5}{8}$ |

10. Electric Strength.

The electric strength shall be determined in accordance with Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials.

Note.—Vulcanized fibre should not be regarded as a satisfactory insulating material when used in damp situations, and in any case should not be subjected to

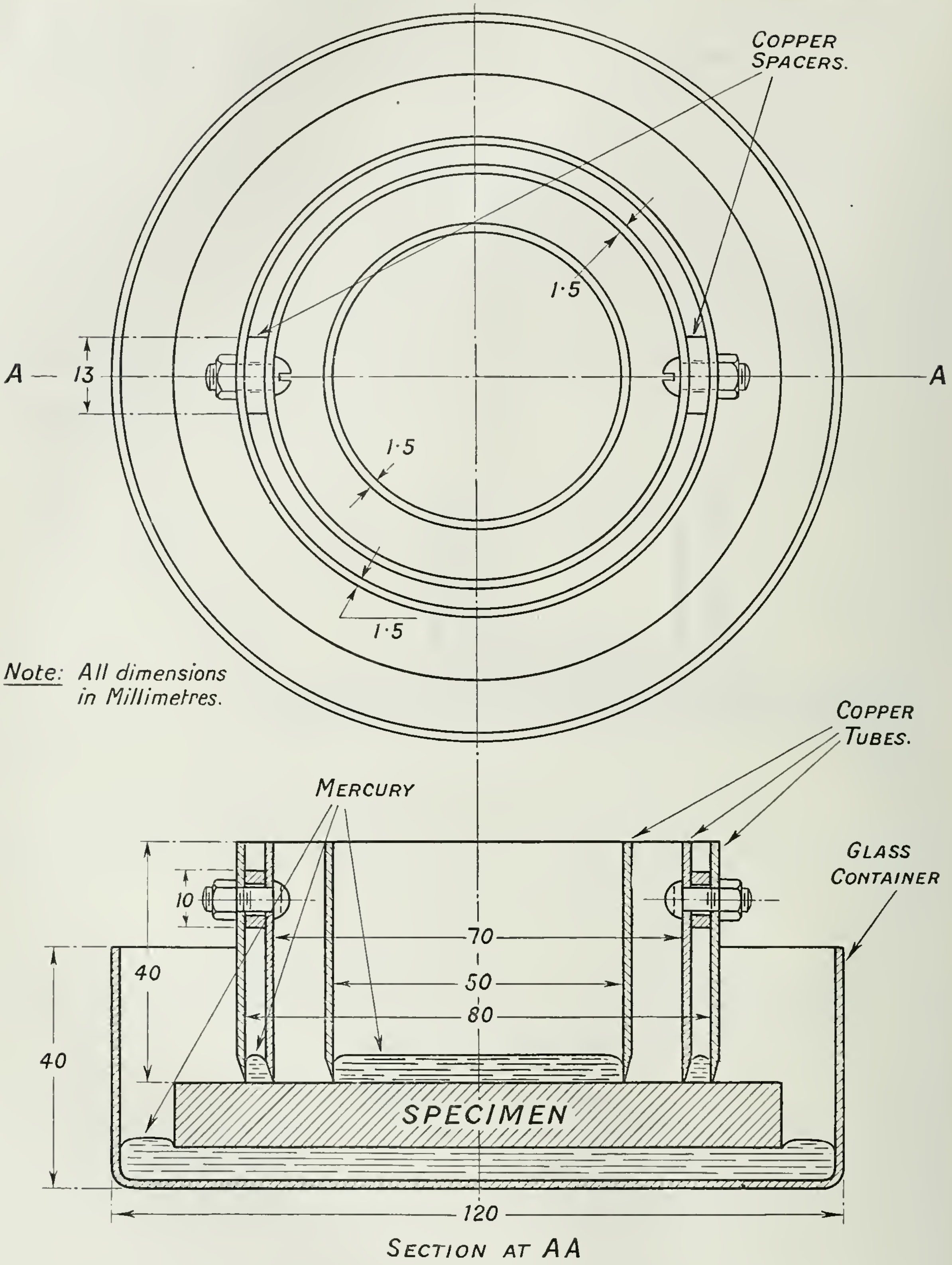


FIG. 12.—Form of Apparatus for Volume Resistivity and Surface Resistivity Tests (U.S. Bureau of Standards).

a permanent working electric stress greater than 25 volts per mil, even when employed in dry situations.

In an acceptance test, the electric strength shall be measured at a temperature of 90° C. after the specimen has been subjected to a controlled atmosphere, relative humidity 75 per cent at a temperature from 15° C. to 25° C. for 18 to 24 hours.

The method of test shall be in accordance with Technical Publication Ref. A/S2.

The test may be carried out under oil when the thickness in relation to the other dimensions is such that the specimen cannot be conveniently punctured in air.

Note.—The specified relative humidity may be obtained by the use of a solution of sulphuric acid in water, specific gravity 1·223.

### 11. Resistivity.

(*a*) *Boards.*

A specimen 4 inches diameter shall be set up for test as shown in Fig. 11. The resistance shall be measured at the end of each minute over a period of 10 minutes electrification at a potential difference of 500 volts. The resistivity shall be expressed in megohms for a centimetre cube, and a curve shall be plotted showing the relationship between resistivity and time.

The specimen shall be tested under the conditions specified in (*c*).

Note.—The dimensions of a suitable apparatus are shown in Fig. 12.

(*b*) *Tubes.*

After closing one end the tube shall be filled with mercury, and tinfoil shall be bound on the outside of the tube with 10 mil binding wire, closely wound over the whole length of the tinfoil. The area of the tinfoil shall be equal to that of the inner electrode used in the resistivity test of a sheet. A guard ring of wire shall be bound round the tube on each side of the tinfoil.

The resistance shall be measured and the resistivity expressed as specified in (*a*).

The specimen shall be tested under the conditions specified in (*c*).

If $L$ = length of tinfoil, cm,
$r_1$ = inner radius of tube, cm,
$r_2$ = outer radius of tube, cm,
$R$ = measured resistance, megohms,
$\rho$ = resistivity, megohms for a cm$^3$,

then
$$\rho = \frac{2\pi RL}{\log_e \frac{r_2}{r_1}}$$

(*c*) *Conditions of Test.*

The material shall be tested under the following conditions :—

(i) After the specimen has been conditioned in accordance with Clause 1.

(ii) After the specimen has been heated for 24 hours at a temperature from 105° C. to 110° C., the resistance being measured at the high temperature. The electrodes shall be raised to the high temperature before the resistance is measured.

(iii) After the specimen has been subjected to a controlled atmosphere, relative humidity not less than 95 per cent at a temperature from 15° C. to 25° C. for 18 to 24 hours, the resistance being measured whilst the specimen is in the controlled atmosphere.

(iv) After the specimen has been subjected to a controlled atmosphere, relative humidity not less than 90 per cent at a temperature from 45° C. to 50° C. for 18 to 24 hours, the resistance being measured whilst the specimen is in the controlled atmosphere. The electrodes shall be raised to the high temperature before the resistance is measured.

### 12. Surface Resistivity.

(*a*) *Boards.*

A specimen 4 inches diameter shall be set up for test as shown in Fig. 13. The surface resistance shall be measured, at the end of each minute over a period of 10 minutes' electrification, at a potential difference of 500 volts. The surface resistivity shall be expressed in megohms for a centimetre square, and a curve shall be plotted showing the relationship between surface resistivity and time.

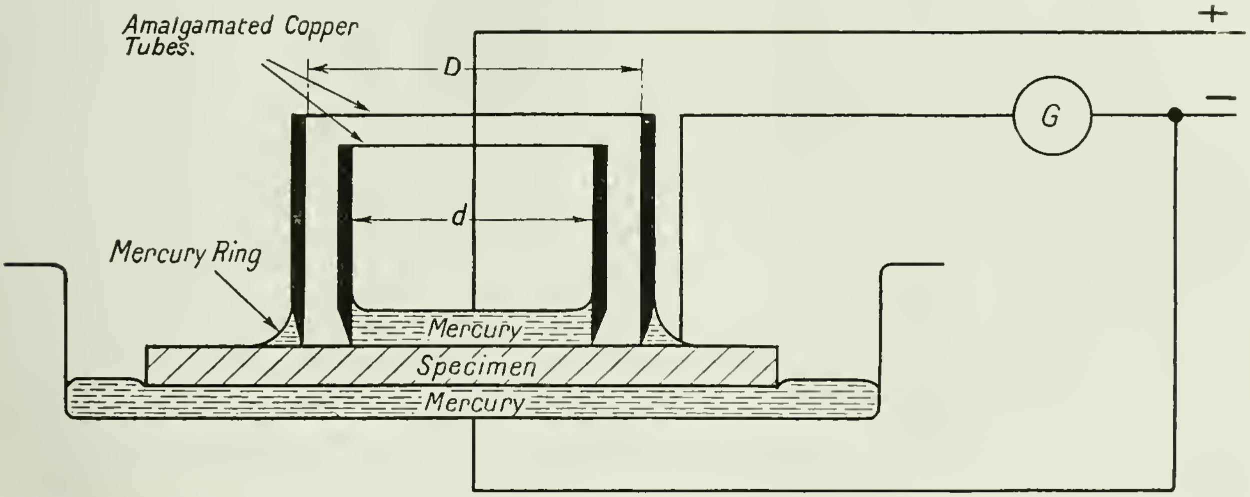


Fig. 13.—Diagrammatic Arrangement of Apparatus for Surface Resistivity Test.

The specimen shall be tested under the conditions specified in (*c*).

NOTE.—If $D - d = 2$ cm, then the surface resistivity $\sigma$ is computed as follows :—

$$\sigma = \frac{R_s \times 2\pi}{\log_e \frac{D}{d}}$$

where $R_s$ = the surface resistance, megohms.

The dimensions of a suitable apparatus are shown in Fig. 12.

(*b*) *Tubes.*

The surface resistance of a tube shall be measured between two 10-mil wires bound tightly round the tube 1 cm apart. The tube shall be filled with mercury to act as a "guard ring."

The surface resistance shall be measured, and the surface resistivity expressed as specified in (*a*).

The specimen shall be tested under the conditions specified in (*c*).

(*c*) *Conditions of Test.*

The material shall be tested after the specimen has been subjected to a controlled atmosphere, relative humidity 75 per cent, at a temperature from 15° C. to 25° C. for 18 to 24 hours, the surface resistance being measured whilst the specimen is in the controlled atmosphere.

NOTE.—The specified relative humidity may be obtained by the use of a solution of sulphuric acid in water, specific gravity 1·223.

### 13. INTERNAL RESISTANCE.

The internal resistance of a board shall be determined as follows :—

Two holes 5 mm diameter shall be drilled to a depth equal to two-thirds of the thickness of the board. The distance between the centres of the holes shall be 15 mm. The holes shall be filled with mercury, and the resistance between them shall be measured at the end of each minute over a period of 10 minutes' electrification, at a potential difference of 500 volts.

The resistance shall be expressed in megohms, and a curve shall be plotted showing the relationship between resistance and time.

The material shall be tested under the conditions specified in Clause 11 (*c*).

In reporting the results of the tests the thickness of the specimen shall be stated.

### 14. SHRINKING, WARPING AND SWELLING.

The tests for shrinkage, warping, and swelling shall be carried out after the specimens have been subjected to a controlled atmosphere, relative humidity 75 per cent, at a temperature from 15° C. to 25° C. for 18 to 24 hours.

NOTE.—The specified relative humidity may be obtained by the use of a solution of sulphuric acid in water, specific gravity 1·223.

(*a*) *Boards.*

A specimen 4 inches square shall be cut from the material and the length, width and thickness measured immediately after conditioning as specified above. Care shall be taken that the specimen is representative of the bulk, and does not include the more highly matured material commonly found on the extreme edges of the board.

The length and width respectively of the specimen shall be the mean of ten measurements taken at points equally spaced along each of two edges at right angles.

The thickness of the specimen shall be the mean of ten measurements of thickness taken at points equally spaced around the edges.

The measurements shall be made by means of a micrometer or other suitable method.

Shrinkage shall be determined by the following methods :—

(*a*) The specimen shall be dried for 48 hours by heating uniformly in an oven at a temperature from 105° C. to 110° C., and the length, width and thickness shall then be measured as above at atmospheric temperature.

Comparison shall be made between the mean values of the dimensions before and after the heat treatment, and the percentage differences computed on the original mean values respectively shall be stated, the original mean values being given.

(*b*) The diameters of a ring approximately 4 inches internal diameter and 6 inches external diameter, shall be measured longitudinally and transversely. The ring shall be immersed in transformer oil complying with British Standard Specification No. 148 for light-grade oil for 120 hours at a temperature from 105° C. to 110° C. The diameters shall then be measured again as before at atmospheric temperature. Comparison shall be made between the values of the diameters before and after the immersion in oil, and the percentage differences computed on the original values shall be stated.

Warping shall be determined by the following method :—

A specimen 6 inches square shall be dried as specified above, and it shall then be placed on a flat surface not less than 7 inches square, and a flat metal plate 6 inches square shall be placed on the specimen, so that the edges of the plate and the specimen coincide. The weight of the upper plate shall not exceed 8 oz. The distances between the four corners of the under surface of the upper plate and the corresponding points on the upper surface of the lower plate shall be measured. The sum of the four readings shall be compared with four times the original mean thickness of the specimen before drying, and the percentage increase computed on four times the original thickness shall be stated.

Swelling shall be determined by the following method :—

The square specimen used in the shrinkage test shall be exposed to a jet of steam for six hours at a temperature from 105° C. to 110° C., and then the thickness shall be re-measured as before. Comparison shall be made between the mean thicknesses before and after the exposure to steam, and the percentage difference computed on the mean thickness after drying shall be stated.

(*b*) *Rods.*

Shrinkage shall be determined by the following method :—

The diameter of a rod, the length of which shall be 4 inches, shall be measured at two points at right angles, one perpendicular to the laminæ and the other parallel to the laminæ of the rod. The rod shall be dried for 48 hours by heating uniformly in an oven at a temperature from 105° C. to 110° C., and the diameter shall then be re-measured at the same points as before at atmospheric temperature.

Comparison shall be made between the mean values of the diameter before and after the heat treatment, and the percentage difference computed on the original mean value shall be stated, the original mean value being given.

Warping shall be determined by the following method :—

A straight rod, the length of which shall be 24 times the diameter, shall be dried for 48 hours by heating uniformly in an oven at a temperature from 105° C. to 110° C. The rod shall then be tested by means of a straight edge or other suitable method, and the maximum deviation from straightness shall be stated, the diameter of the rod being given.

(*c*) *Tubes.*

Shrinkage shall be determined by the following method :—

The internal and external diameters of a tube, the length of which shall be 4 inches, shall be measured in two directions at right angles. The tube shall be dried as specified in (*b*) above, and the diameters shall then be re-measured at the same points as before.

Comparison shall be made between the mean values of the internal and external diameters respectively before and after the heat treatment, and the percentage differences computed on the original mean values shall be stated, the original mean values being given.

Warping shall be determined by a method similar to that described in (*b*) above. The length of the tube shall be 24 times the internal diameter. When expressing the results of the test the internal and external diameters shall be given.

### 15. Machining Properties.

The machining properties of the material shall be determined by shaping it in a shaping machine and by turning, milling and punching specimens. The effect on the material with respect to cracking, splitting, chipping or raggedness shall be stated.

Boards shall be tested by being tapped with a No. 0 B.A. tap. Rods and tubes shall be tested by being screwed, externally and internally, in the case of tubes, with 11 B.S.W. threads per inch, cut with a tool by an operator experienced in working with this class of material. The effect on the material with respect to cracking, splitting, chipping or raggedness shall be stated.

Note.—The manufacturer of the material should be asked to state the cutting speed, depth of cut, rate of feed, and lubricant, if any, to be employed in carrying out the machining tests.

### 16. Freedom from Chemical Reaction.

The material cut into small pieces shall be tested for freedom from acids and alkalis in the following manner :—

Cut up 30 to 40 grammes of the dried sample into pieces, weigh off duplicate lots of 10 grammes each, introduce each into a $\frac{1}{4}$ litre flask, add to each 200 $cm^3$ distilled water. Boil for 20 minutes, decant the solution through a perforated disc, wash each lot of the material twice with 75 $cm^3$ of warm water. Titrate filtrates, using methyl orange indicator.

If the indicator shows the solution to be alkaline, titrate (neutralize) it with a standard centinormal solution of sulphuric acid—

$$\frac{N}{100}H_2SO_4$$

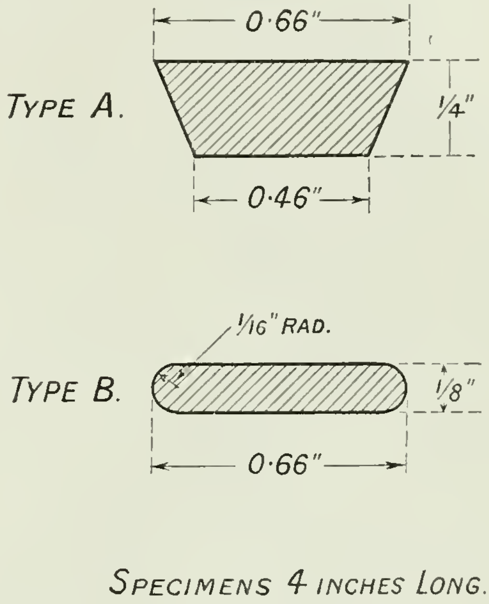


Fig. 14.—Specimens for Slot Wedge Test.

If it shows the solution is acid titrate (neutralize) it with a standard centinormal solution of sodium hydrate—

$$\frac{N}{100}NaOH$$

or potassium hydrate—

$$\frac{N}{100}KOH$$

In either case the number of $cm^3$ of the reagent required to neutralize 10 grammes of the material shall be stated.

When the material is thicker than $\frac{1}{2}$ inch, the test shall be made on drillings obtained from the central portion of the material.

Note.—The above test only indicates mineral acidity. If the total acidity of the material is required, including organic acids which may be present, the method outlined should be slightly modified by boiling in methylated spirit instead of distilled water, and by titrating with phenol-phthalein in place of methyl orange.

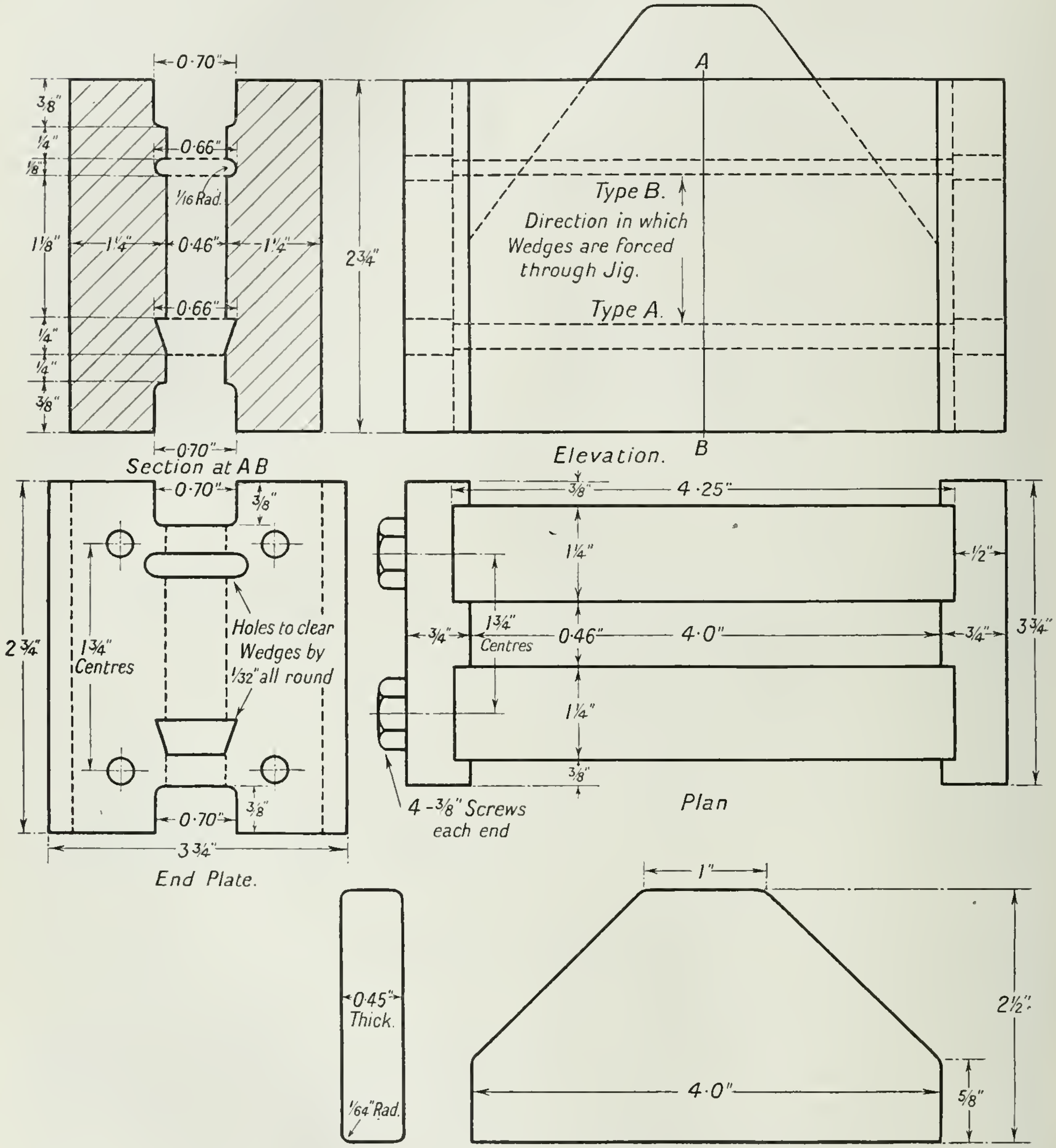


Fig. 15.—Form of Jig for Slot Wedge Test.

### 17. FREEDOM FROM CONDUCTING PARTICLES AND PINHOLES.

These tests shall be made by one of the following methods :—

(*a*) *Thick Materials.*

In the case of materials thicker than 1/16 inch, a specimen 6 inches × 4 inches shall be photographed by X-rays. The number of metallic particles and pinholes per square foot shall be stated.

(*b*) *Thin Materials.*

In the case of materials up to and including 1/16 inch thick, specimens not less than 12 inches square shall be tested by the following method :—

The specimen shall be dipped into a 1 per cent solution by volume of acetic acid, and then allowed to air-dry for one hour while lying flat on a cloth.

When dry the specimen shall be dipped again in a solution containing 0·1 $cm^3$ acetic acid and 0·1 gramme of potassium ferricyanide in 100 $cm^3$ distilled water.

Each metallic iron particle will produce a blue spot on the specimen, and each copper, brass or gunmetal particle a red spot.

The number of blue and red spots respectively per square foot of the specimen shall be stated.

NOTE.—The potassium ferricyanide solution should be tested before use with some precipitated ferric hydroxide dissolved in strong nitric acid, and diluted with water. The potassium ferricyanide solution should give no blue precipitate or coloration.

### 18. EFFECT OF OIL.

A specimen shall be immersed in transformer oil complying with B.S.S. No. 148 for light-grade oil for seven days continuously at a temperature from 105° C. to 110° C. The condition of the specimen shall be stated with respect to warping, splitting, blistering, softening or other deterioration after immersion.

### 19. ABSORPTION OF WATER.

The specimen shall be conditioned in accordance with Clause 1 before the test for water absorption is carried out.

A sample of board $1\frac{1}{2}$ inches square, or a rod or tube $1\frac{1}{2}$ inches long, shall be weighed. The board specimen shall have the four edges, and the rod or tube specimen the two ends freshly cut before being used for the test. The specimen shall then be immersed in water at a temperature from 15° C. to 25° C. After 24 hours' immersion it shall be taken from the water, and, after removing the surface moisture by wiping, weighed again.

The specimen shall then be replaced in the water, and after six days' immersion reweighed with the same precautions as before. The weight shall be taken to the nearest milligramme in each case.

The percentage absorption of water in each case shall be computed on the original weight of the specimen ; and the original dimensions of the specimen shall be stated.

When it is desired to distinguish between the absorption in the longitudinal, transverse and perpendicular directions respectively, the appropriate surfaces of the specimen shall be coated with a waterproof varnish before the test for water absorption is carried out.

### 20. SLOT WEDGE TEST.

To ascertain the suitability of vulcanized fibre for the manufacture of slot wedges for electrical machines the following test shall be carried out after the specimen has been conditioned in accordance with Clause 1.

A specimen shall be machined from the 4-inch square sample used in the shrinkage test to one of the dimensions shown as types A and B in Fig. 14, and shall be inserted into a special jig, shown in Fig. 15, representing a machine slot. The specimen shall be forced radially out of the slot in a compression testing machine, and the pressure required, per inch of length, to displace the wedge shall be determined.

### 21. FREEDOM FROM CONDUCTING PARTICLES (FOR MATERIAL IN ROLLS ONLY).

The vulcanized fibre shall be drawn at a speed of approximately two feet per minute between a metallic plate and a system of overlapping rollers as specified in Clause 15 of Technical Publication Ref. A/S5.

An alternating potential difference (50 cycles), of 50 volts per mil thickness of the vulcanized fibre, shall be applied between the plate and the rollers.

The number of punctures per square yard shall be stated.

On a failure occurring the defective spot shall be marked and the vulcanized fibre then drawn back and passed through a second time. The ability of the part originally defective to pass test on the second application shall be noted.

# DIRECTIONS FOR THE STUDY OF ELECTRICAL INSULATING PAPERS (UNVARNISHED)* FOR PURPOSES OTHER THAN THE MANUFACTURE OF CABLES.

[Revised Report (Ref. A/S5)† received from the British Electrical and Allied Industries Research Association.]

## Contents.

Page
Index .. .. .. .. .. .. 982
Preface .. .. .. .. .. .. 983
I. Definitions .. .. .. .. .. 984
II. Processes of Treatment during Manufacture .. 985
III. Tests .. .. .. .. .. .. 986
IV. Schedule of Uses and Tests .. .. .. 996

(This schedule indicates which tests are most appropriate for papers intended for the various specific applications shown.)

Appendix.. .. .. .. .. .. 996

## Index

Absorption : floating test . . . . . . . . 989
Acid, treatment with (parchmentising) . . . . . 985
Acidity, test for . . . . . . . . . . . 989
Ageing, test for . . . . . . . . . . . 988
Alcohol, treatment of cellulose with . . . . . 985
Alkali, treatment with (parchmentising) . . . . . 985
Alkalinity, test for . . . . . . . . . . 989
Alum, use in rosin sizing . . . . . . . . 985
Aluminium sulphate, use in rosin sizing . . . . . 985
Aniline dyes, use of, in colouring process . . . . 985
Animal sizing (*see* Gelatine sizing) . . . . . . 985
Ash, test for mineral ash . . . . . . . . 989
Aspirator bottle, for porosity test . . . . . . 988

Beeswax, use of, in glazing. . . . . . . . 986
Best rag tissue paper, definition of . . . . . . 984
Bleaching, definition of . . . . . . . . . 985
Brine, treatment of cellulose with . . . . . . 985
Brokes, use of, in process of loading . . . . . 985
*Broussonetia papyrifera*, use of, in tissue paper . . 985
Burette, for porosity test . . . . . . . . 988
Bursting strength, determination of . . . . . . 988
Bursting test . . . . . . . . . . . . 988

Calcium sulphate, use of, in loading . . . . . 985
Carbon disulphide, treatment of cellulose with . . 985
Cartridge paper, note on . . . . . . . . 984
Casein, use of, in gelatine sizing . . . . . . 985
Casein, determination of . . . . . . . . 992
Cellulose, use of, in viscose sizing . . . . . . 985
Chemical tests. . . . . . . . . . . . 989
Chemical test, for metallic particles . . . . . . 992
Chemical wood pulp, definition of . . . . . . 984
China clay, use of, in loading . . . . . . . 985
Chloride of lime, use of, as bleaching agent . . . 985
Cochineal, for producing whiteness . . . . . . 985
Colouring, definition of . . . . . . . . . 985
Condenser tissue paper, definition of . . . . . 984
Conditioning of specimens for test . . . . . . 986
Conducting particles, flash test for . . . . . . 992
Controlled atmosphere, for conditioning . . . . 986
Copper, polished, for plate glazing . . . . . . 986
Core plate insulating paper, definition of . . . 984
Cotton tissue paper, definition of . . . . . 984

Definitions, of papers . . . . . . . . . . 984
Density, determination of . . . . . . . . . 986
Direction test . . . . . . . . . . . . 996

Electrical tissue paper, definition of . . . . . 984
Engine sizing (*see* Rosin sizing) . . . . . . . 985
Extension, test for . . . . . . . . . . 986

Fibrous material, identification of . . . . . . 993
Fish paper, definition of . . . . . . . . . 984
Flash test for conducting particles . . . . . . 992
Flash test, voltage for . . . . . . . . . 992
Floating test for absorption . . . . . . . . 989
Frequency of current for flash test . . . . . . 992

Gelatine sizing, process of . . . . . . . . 985
Glazing, friction . . . . . . . . . . . 985
Glazing, machine . . . . . . . . . . . 985
Glazing, methods of . . . . . . . . . . 985
Glazing, plate . . . . . . . . . . . . 986
Glue, emulsification of, with ether . . . . . . 992
Glue, use of, in gelatine sizing . . . . . . . 985
Grass bleached tissue paper . . . . . . . . 984
Greaseproof, treatment for making . . . . . . 985

Hand-made tissue paper . . . . . . . . . 985
Hard sizing (*see* Rosin sizing) . . . . . . . 985
Horn fibre paper, definition of . . . . . . . 984
Humidity of controlled atmosphere . . . . . . 986
Hydra-cellulose (*see* Hydration) . . . . . . . 985
Hydration, process of . . . . . . . . . . 985
Hydro-cellulose (*see* Parchmentising). . . . . . 985

Identification of fibres . . . . . . . . . 993
Imitation Japanese tissue paper, definition of . . 985
Insulation, failure of, in flash test . . . . . . 993
Iodine, use of, in preparation of stain . . . . 993
Iron particles, in rope paper . . . . . . . 984

Japanese Gampi tissue paper, definition of . . . 985
Japanese Kodzu tissue paper, definition of . . . 985

---

* The term "unvarnished" denotes that the paper has not been varnished or impregnated with insulating compounds, but embraces material which has been subjected to preparatory treatments such as those referred to in Section II.

† This Report supersedes the Report (Ref. A/S1) published on pages 657 to 670 of Vol. 60 of the *Journal*.

Page
Japanese Mino dental tissue paper, definition of . . 985
Japanese Tosa tissue paper, definition of . . . 985
Jute fibre, use of, in paper. . . . . . . 984
Jute paper, definition of . . . . . . . . 984

Kaolin, use of in loading . . . . . . . . 985
Kjeldahl, method for determination of nitrogen . . 992
Kraft paper, definition of . . . . . . . . 984

" L " piece, use of, in tearing test . . . . . . 988
Leather paper, definition of . . . . . . . 984
Lime rag-pulp paper, definition of . . . . . 984
Loading, process of . . . . . . . . . 985

Machine finish, definition of . . . . . . . 986
Manilla fibre paper, definition of . . . . . . 984
Manilla paper, definition of. . . . . . . . 984
Mechanical wood-pulp paper, definition of . . . 984
Metallic particles, chemical test for . . . . . 992
Metallic particles, in rope paper . . . . . 984
Micro-photographs, reproduction of, showing fibres . 993
Microscopical examination of fibres . . . . . 993
Mill finish (*see* Machine finish) . . . . . . 986
Mineral ash, test for . . . . . . . . . 989
Mineral pigments, use of, in colouring process . . 985
Moisture loss on drying . . . . . . . . 989

Nitrogenous material, determination of . . . . 992

Paper, definition of . . . . . . . . . . 984
Paper mulberry, use of, in tissue paper . . . . 985
Paraffin wax, use of, in glazing. . . . . . 985
Parchmentising, process of . . . . . . . . 985
Porosity, test for . . . . . . . . . . 988
Potassium hydrate, in acid test. . . . . . 989
Potassium iodide, in preparation of stain . . . 993

Rag bank paper, definition of . . . . . . . 984
Rag bond paper, definition of . . . . . . . 984
Rags, cotton, use of, in papers . . . . . . . 984
Rags, linen, use of, in papers . . . . . . . 984
Ream, number of sheets in . . . . . . . 984
Red rope paper (*see* Rope paper) . . . . . 984
Resinous materials, determination of . . . . 992
Resins, ether-soluble . . . . . . . . . 992
Rollers, for flash test . . . . . . . . . 992
Rope paper, definition of . . . . . . . . 984
Rosin sizing, process of . . . . . . . . 985
Rosin, treatment of pulp with . . . . . . . 985

Schedule of tests . . . . . . . . . . . 996
Silversmiths' tissue paper, definition of . . . . 984
Sizing, process of . . . . . . . . . . 985
Soda rag-pulp paper, definition of . . . . . 984
Soda wood-pulp paper, definition of . . . . 984
Sodium chloride, removal of glue with . . . . 992
Sodium hydrate, treatment of cellulose with . . . 985
Sodium hydrate, use of, in acid test . . . . 989
Sodium resinate, use of, in sizing . . . . . 985
Soft sizing (*see* Gelatine sizing) . . . . . . 985
Stain, zinc-chloride-iodine . . . . . . . . 993
Staining, definition of . . . . . . . . . 985
Sulphate wood-pulp paper, definition of . . . . 985
Sulphite imitation Japanese tissue paper, definition of 985
Sulphite tissue paper, definition of . . . . . 985
Sulphite wood-pulp paper, definition of . . . . 984
Sulphuric acid, for alkalinity test . . . . . 989

Page
Sulphuric acid, for controlled atmosphere . . . 986
Super-calendering, process in glazing . . . . 986
Superfine litho paper . . . . . . . . . 986

Tearing strength, test for . . . . . . . . 988
Tensile strength, test for . . . . . . . . 986
Tests . . . . . . . . . . . . . 986
Thickness, determination of . . . . . . . 986
Tissue paper, definition of . . . . . . . . 984
Treatment, processes of, in manufacture . . . 985
Tub sizing (*see* Gelatine sizing) . . . . . . 985

Ultramarine, for producing whiteness . . . . 985

Viscose sizing, process of . . . . . . . . 985
Voltage, for flash test . . . . . . . . . 992

*Wickstroemia puciflora*, use of, in tissue paper . . 985

Zinc chloride, use of, in treating paper . . . . 984
Zinc-chloride-iodine stain, composition and preparation of 993

## PREFACE.

As the result of the experience gained since the issue of Technical Publication Ref. A/S1, it has been found desirable to modify several of the Clauses and to add a test for Absorption. This test is intended to indicate the ability of paper to absorb oil or varnish in a direction normal to the surface.

The temperature at which specimens are conditioned has been altered to 20° C.; and the clauses for the determination of thickness and density have been simplified.

In order to avoid discrepancies in the results obtained in the porosity test, due to the variation of the air pressure, this test has been modified by ascertaining the time required for a constant volume (100 $cm^3$) of water to flow out of the burette.

The procedure for determining the acidity, alkalinity, and the amount of resinous material in the paper respectively has been improved, and a slight modification made in the test for nitrogenous material. The amount of paper to be employed in the mineral ash test has been reduced to 5 grammes.

In Technical Publication Ref. A/S1, three tests were inserted for detecting metallic particles with a view to gaining experience on the relative efficacy of the tests. It has been found that the old test (*c*) is the most satisfactory test, and the other two have therefore been deleted.

It is now found that there is no necessity for a clause dealing with crinkling under tension.

The method for determining the directions of the " length " and the " width " of paper suggested in the Appendix to Ref. A/S1 was not applicable to thick papers, and another method has therefore been adopted which is suitable for all thicknesses of paper.

In the Schedule the various purposes for which papers are employed have been reclassified with a view to the simplification of the tests that are applicable to papers for different uses. The Schedule of papers employed for particular purposes has been deleted, as with improvements resulting from this research the Schedule no longer represents the state of the art.

It is anticipated that in the near future the Association will be in a position to make recommendations to the British Engineering Standards Association for the issue of a Purchasing Specification for Electrical Insulating Papers (Unvarnished).

The Director of the E.R.A. will value comments and criticism from those who have occasion to use any of the tests given in this Specification.

## I. DEFINITIONS.

In order to avoid the ambiguity associated with many of the terms in use in the paper trade, it is recommended that in defining papers for electrical purposes the following terms be adopted and that their use be confined to the materials described :—

*Paper.*

The term " Paper " denotes a matted or felted structure of fibrous material formed into a relatively thin sheet on a paper-making machine.

*Pure Manilla Fibre Paper.*

The term " Pure Manilla Fibre Paper " denotes paper made from Manilla Fibre only.

*Note.*—The best paper would be made from new fibre.

*Manilla Paper.*

The term " Manilla Paper " denotes a strong paper made from Sulphite Wood Pulp, but may contain some manilla and hemp fibre.

*Note.*—This paper is occasionally described as " Cartridge Paper."

*Rope Paper.*

The term " Rope Paper " denotes paper made from rope-ends.

*Note I.*—Rope paper is liable to contain iron particles.

*Note II.*—" Manilla " paper dyed red is sometimes designated " Red Rope Paper."

*Chemical Wood-Pulp.*

The term " Chemical Wood-Pulp " denotes wood-pulp prepared by a chemical process, as, for example, sulphate, sulphite and soda wood-pulp described below.

*Sulphate Wood-Pulp (Kraft) Paper.*

The terms " Sulphate Wood-Pulp Paper " and " Kraft Paper " denote paper made from wood-pulp only, by the sulphate process.

*Sulphite Wood-Pulp Paper.*

The term " Sulphite Wood-Pulp Paper " denotes paper made from wood-pulp only, by the sulphite process.

*Soda Wood-Pulp Paper.*

The term " Soda Wood-Pulp Paper " denotes paper made from wood-pulp only by the caustic soda process.

*Note.*—Paper made by this process is a soft and bulky paper.

*Mechanical Wood-Pulp Paper (Core plate insulating paper).*

The term " Mechanical Wood-Pulp Paper " denotes paper made from wood by the mechanical pulping process.

*Jute Paper (Horn Fibre Paper).*

The term " Jute Paper " denotes paper made from jute fibre without subsequent treatment with chemicals.

*Soda Rag-Pulp Paper.*

The term " Soda Rag-Pulp Paper " denotes paper made from rags only, by the caustic soda process.

*Lime Rag-Pulp Paper.*

The term " Lime Rag-Pulp Paper " denotes paper made from rags only, by the lime and carbonate of soda process.

*Rag Bond Paper.*

The term " Rag Bond Paper " denotes paper made from linen and cotton rags only, and weighing more than 13 lb. per ream (480 sheets), post size (21 in. × 16½ in.).

*Rag Bank Paper.*

The term " Rag Bank Paper " denotes paper made from linen and cotton rags only, and weighing not more than 13 lb. per ream (480 sheets), post size (21 in. × 16½ in.).

*Leather Paper (Fish Paper).*

The term " Leather Paper " denotes paper made from cotton rags only, and afterwards chemically treated (generally with zinc chloride) so that a homogeneous sheet of converted cellulose (Amyloid) is produced.

*Tissue Paper.*

The term " Tissue Paper " denotes paper of which the weight of 2 000 square feet does not exceed about 9 lb.

*Best Rag Tissue (Condenser or Electrical Tissue) Paper.*

The terms " Best Rag Tissue Paper," " Condenser Tissue Paper " and " Electrical Tissue Paper " denote tissue paper made from rags only.

*Note.*—The term " Electrical Tissue Paper " is generally used for the heavier grades.

*Cotton Tissue Paper.*

The term " Cotton Tissue Paper " denotes tissue paper made from cotton rags only.

*Silversmiths' Tissue Paper.*

The term "Silversmiths' Tissue Paper" denotes tissue paper made from rags only, grass bleached, and free from chemicals and loading material.

> *Note.*—In order to ensure that Silversmiths' Tissue Paper does not contain chemicals, it is necessary to obtain a guarantee that it has been grass bleached and is free from chemicals.

*Sulphite Tissue Paper.*

The term "Sulphite Tissue Paper" denotes tissue paper made from wood-pulp by the sulphite process, but may contain some rag pulp.

*Sulphite Imitation Japanese Tissue Paper.*

The term "Sulphite Imitation Japanese Tissue Paper" denotes soft porous tissue paper made from wood-pulp by the sulphite process.

*Japanese Gampi Tissue Paper.*

The term "Japanese Gampi Tissue Paper" denotes tissue paper hand-made from the *Wickstroemia puciflora*.

*Japanese Kodzu Tissue Paper.*

The term "Japanese Kodzu Tissue Paper" denotes tissue paper made from the *Broussonetia papyrifera* (Paper mulberry).

> *Note.*—Two qualities of this paper are in general use.

*Japanese Tosa Dental Tissue Paper.*

The term "Japanese Tosa Dental Tissue Paper" denotes soft porous tissue paper made from the *Broussonetia papyrifera* (Paper mulberry) in the Tosa district.

> *Note.*—This paper is superior to the Mino Dental Tissue.

*Japanese Mino Dental Tissue Paper.*

The term "Japanese Mino Dental Tissue Paper" denotes soft porous tissue paper made from the *Broussonetia papyrifera* (Paper mulberry) in the Mino district.

> *Note.*—This paper is inferior to the Tosa Dental Tissue.

## II. PROCESSES OF TREATMENT DURING MANUFACTURE.

During manufacture the papers defined above are subjected to one or more of the processes described below :—

*Bleaching.*

Bleaching is carried out on the pulp before it is made into paper. The usual agent is chloride of lime.

*Loading.*

Loading consists of filling up the interstices between the fibres to impart appearance and weight. The usual substances employed are Kaolin (china clay), calcium sulphate and "brokes."

> *Note.*—The term "brokes" includes spoiled, imperfect or waste paper which is capable of being remanufactured.

*Colouring.*

The term "Colouring" denotes the production of *coloured* pulp, or a pure (or toned) *white* pulp, after it has been bleached. The colour is produced by the addition of either mineral, or other pigments or aniline dyes, to the pulp. Whiteness is produced by the addition of ultramarine or cochineal to the pulp for the best papers, and aniline blues for the cheaper papers.

*Staining.*

The term "Staining" denotes applying a coating of dye to the surface of the paper.

*Sizing.*

The term "Sizing" denotes a process employed to increase the water-resisting property of the paper.

Three principal sizing treatments are employed as follows :—

(*a*) *Rosin* (*or Engine*) *Sizing* (*Hard Sizing*).

Rosin Sizing is carried out by the addition of rosin to the pulp in the form of sodium resinate, and alum in the form of aluminium sulphate.

(*b*) *Viscose Sizing.*

Viscose Sizing is carried out by the addition of viscose to the pulp with or without rosin.

> *Note.*—Viscose is made from cellulose in the form of bleached cotton or wood pulp by treatment with sodium hydrate and then with carbon disulphide, which converts the cellulose into a gelatinous transparent mass soluble in water. The crude solution thus obtained is refined by treatment either with saturated brine or with alcohol.

(*c*) *Gelatine* (*or Animal or Tub*) *Sizing* (*Soft Sizing*).

Gelatine Sizing is carried out by coating the finished paper with gelatine, glue or casein.

*Parchmentising* (*Hydro-Cellulose*).

The term "Parchmentising" denotes an acid treatment so as to render the paper grease-proof.

*Hydration* (*Hydra-Cellulose*).

The term "Hydration" denotes the incorporation of water with the fibres producing a kind of gelatinous film. This result is obtained by beating the pulp in a suitable manner for a sufficiently long time. This process is used in the production of grease-proof and similar papers.

*Glazing.*

Four methods of glazing are employed, as follows:—

(*a*) *Machine Glazing* (*M.G.*).

Machine Glazing is carried out by passing the paper over a hot cylinder during the course of manufacture. One side of the paper only is machine glazed.

(*b*) *Friction Glazing* (*F.G.*).

Friction Glazing is carried out by passing the paper between warm cylinders which are treated with either beeswax or paraffin wax.

(*c*) *Super-Calendering* (*S.C.*).

Super-Calendering is carried out by passing the paper through a machine consisting of a stack of cylinders (4–12) of polished steel and compressed paper or cotton, arranged alternately, the former being heated. The paper is usually damped before passing through the super-calender.

(*d*) *Plate Glazing* (*P.G.*).

Plate Glazing is carried out by placing the paper between plates of polished metal and subjecting them to pressure.

> *Note.*—Plate glazing is chiefly confined to hand-made papers, superfine litho papers and the like.

*Machine Finish* (*M.F.*).

When paper is not glazed, a slightly smooth surface is imparted to it during its travel through the paper-making machine. This is known as machine or mill finish.

## III. TESTS.

The tests given below are recommended for the study of Electrical Insulating Papers (Unvarnished).

The Schedule at the end of the Specification indicates which tests are most appropriate for papers intended for the various specific applications shown.

| Clause No. | Schedule of Tests |
|---|---|
| 1 | Conditioning of Specimens for Test. |
| 2 | Determination of Thickness. |
| 3 | Determination of Density. |
| 4 | Tensile Strength and Extension. |
| 5 | Ageing (Bursting Test). |
| 6 | Tearing Strength. |
| 7 | Porosity. |
| 8 | Absorption: Floating Test. |
| 9 | Moisture loss on drying at 100° C. |
| 10 | Acidity and Alkalinity. |
| 11 | Mineral Ash. |
| 12 | Resinous Material. |
| 13 | Nitrogenous Material. |
| 14 | Chemical Tests for Metallic Particles. |
| 15 | Flash Tests for Conducting Particles. |
| 16 | Microscopical Examination. |

### 1. CONDITIONING OF SPECIMENS FOR TEST.

Before the tests specified in Clauses 3, 4, 5, 6, 7, 8 and 9 are carried out, single sheets of paper shall be conditioned in a controlled atmosphere for not less than 18 hours. The controlled atmosphere shall have a relative humidity of 75 per cent and a temperature of 20° C. (68° F.).

The specified relative humidity may be obtained by the use of a solution of sulphuric acid in water, specific gravity 1·223.

The paper shall be tested as soon as possible after removal from the controlled atmosphere, and in any case before 3 minutes have elapsed.

> *Note.*—The method of conditioning given above cannot be applied to rolls of paper. The specimens must be cut from the rolls before conditioning.

### 2. DETERMINATION OF THICKNESS.

The thickness of the paper shall be measured by means of a micrometer of a suitable type which shall be stated in the report of the tests.

The average thickness of the paper shall be ascertained as follows:—

In the case of rolls, after the three outer layers have been removed a test-piece one foot long and the full width of the roll shall be taken. Ten measurements of thickness equally spaced diagonally across the test-piece shall be made.

In the case of sheets, ten measurements of thickness equally spaced diagonally across the sheet shall be made.

The maximum, minimum and mean values of thickness shall be stated.

### 3. DETERMINATION OF DENSITY.

The paper shall be conditioned in accordance with Clause 1 before the density is determined.

The density expressed in terms of weight in grammes per cubic centimetre shall be determined by weighing and measuring a specimen about 8 inches (20 cm) square immediately after it has been conditioned as specified in Clause 1.

### 4. TENSILE STRENGTH AND EXTENSION.

The paper shall be conditioned in accordance with Clause 1 before the tests for tensile strength and extension are carried out.

For the purpose of the test for tensile strength and extension at least 12 samples for test shall be taken. Six of these shall be cut in the direction of the length of the paper and six across the width of the paper.

The dimensions of each test-piece shall be $\frac{5}{8}$ inch wide by 10 inches long so as to give 6 inches clear between the testing jaws.

The load shall be applied gradually, and the test shall be carried out in such a manner that the tensile strength in lb. per square inch (kg per sq. cm) sectional area, and the percentage extension on the original length under load, can be determined.

In computing the tensile strength of the paper the mean thickness obtained in accordance with Clause 2 shall be taken.

The maximum, minimum and mean values of tensile strength and of percentage extension shall be stated.

For the method of determining the direction of "length" and "width" of paper when supplied in sheets, see Appendix.

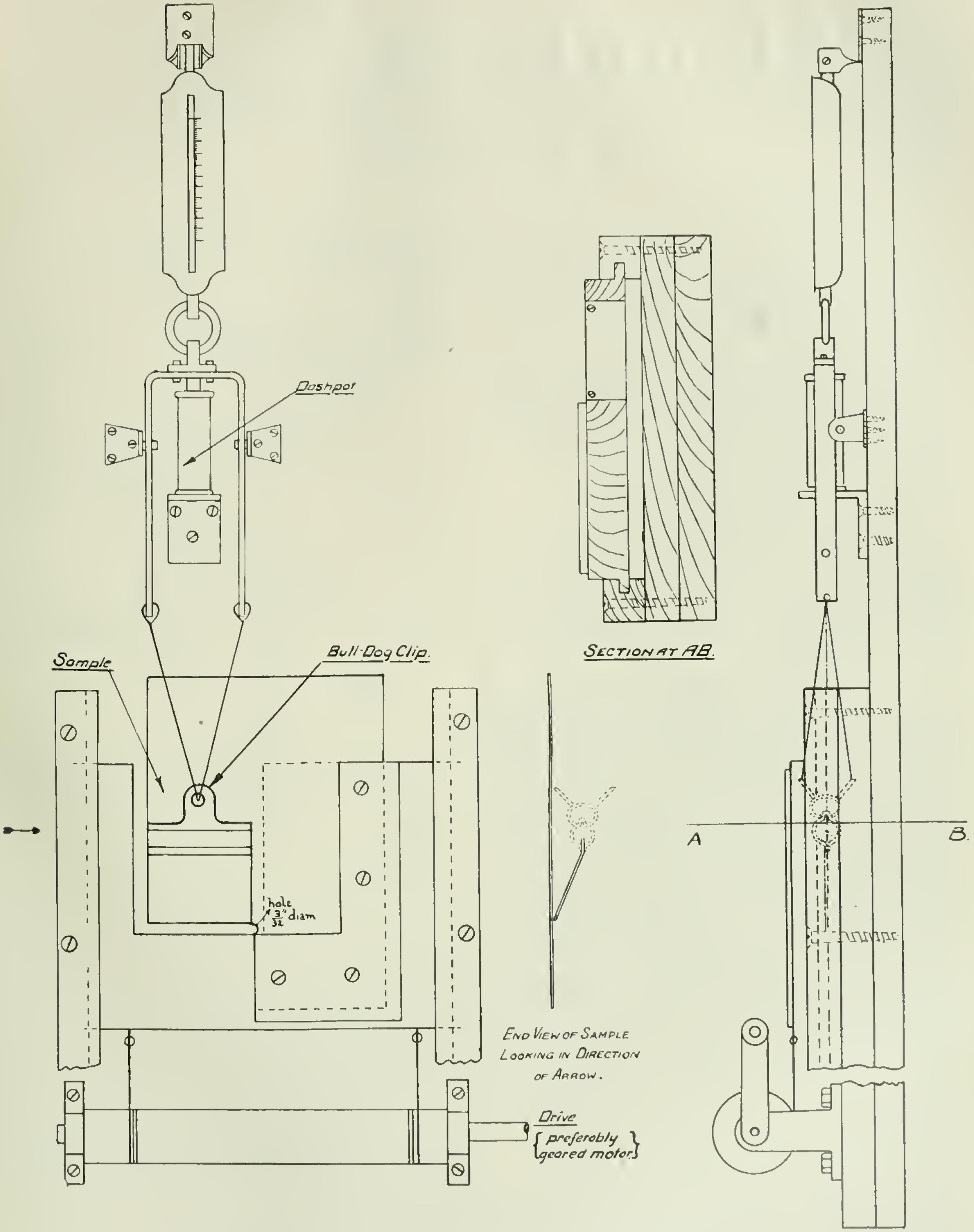

Dashpot
Sample
Bull-Dog Clip
hole $\frac{3}{32}$" diam
Section at AB.
A
B.
End View of Sample Looking in Direction of Arrow.
Drive
{preferably geared motor}

Fig. 1.—Apparatus for Measuring the Tearing Strength of Paper.

### 5. Ageing (Bursting Test).

The tendency of the paper to deteriorate with age shall be proved by a comparison of the bursting strength of the paper before and after it has been heated in a drying oven at a temperature of 110° C. (230° F.) for 24 hours. The paper shall be conditioned in accordance with Clause 1 before the bursting test is carried out in each case. The bursting strength of the paper shall be determined in accordance with the following method :—

The paper shall be gripped on to a ring leaving a free circular membrane which shall be subjected to fluid pressure until it is broken. The value of the pressure required to break the paper, shown on an indicator attached to the apparatus, shall be expressed in lb. per square inch (kg per sq. cm).

This value is defined as the bursting strength of the paper.

The bursting strength of the paper shall be measured at ten positions equally spaced diagonally across a test-piece one foot long and the full width of the roll, when the paper is submitted in a roll, and at ten positions equally spaced diagonally across a sheet, when the paper is submitted in sheets.

The maximum, minimum and mean values of the bursting strength shall be stated.

The direction in which the paper commences to break with respect to the length of the paper shall be noted.

For the method of determining the direction of "length" and "width" of paper when supplied in sheets, see Appendix.

### 6. Tearing Strength.

The paper shall be conditioned in accordance with Clause 1 before the tearing strength test is carried out.

The resistance to tearing shall be proved by the load required to tear the paper commencing from a hole 3/32 inch diameter punched out of the paper. The position of the hole and application of the load shall be as shown in Fig. 1.

The size of each separate specimen tested shall be 6 inches square.

(*a*) Three tests shall be made with the tear in the direction of the length of the paper. This shall be called the "Length Tear Test."

(*b*) Three tests shall be made with the tear across the width of the paper. This shall be called the "Width Tear Test."

For the method of determining the direction of "length" and "width" of paper when supplied in sheets, see Appendix.

The method of carrying out the tearing test shall be as follows :—

Prepare the paper specimen as shown in Fig. 1.

Swing the inverted "L" piece to the right.

Place the paper in position, the punched hole being at the edge of the "L" piece as indicated.

Screw the "L" piece down. Bend over the cut piece, and attach grip device—needle or clip—and secure to lower portion of balance.

Rotate the winding gear with steady movement at a rate of approximately 12 inches per minute until the 6-inch length is torn through. (A motor drive is recommended.)

Watch the balance and average the slightly varying values of the pull observed.

The maximum, minimum and mean values of the "length" and "width" tearing strengths respectively shall be stated.

### 7. Porosity.

The paper shall be conditioned in accordance with Clause 1 before the porosity test is carried out.

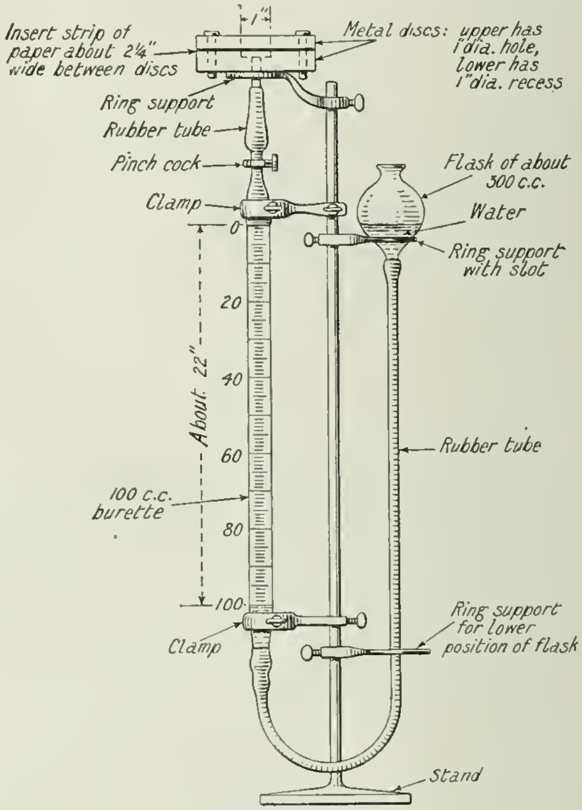

1"
Insert strip of paper about 2¼" wide between discs
Metal discs: upper has 1"dia. hole, lower has 1"dia. recess
Ring support
Rubber tube
Pinch cock
Flask of about 500 c.c.
Clamp
Water
0
Ring support with slot
20
About 22"
40
60
Rubber tube
100 c.c. burette
80
100
Ring support for lower position of flask
Clamp
Stand

Fig. 2.—Apparatus for Measuring the Porosity of Paper.

The porosity of the paper shall be determined by means of the following apparatus, which shall be assembled as shown in Fig. 2.

Glass burette graduated 0 to 100 cc (length of 100 cc graduations approximately 22 inches) and fitted with a stopcock at top.

Two metal clamping discs having 1 inch recess in one and 1 inch hole in the other. The inner side of each disc shall be faced with sheet rubber 1/32 inch thick.

Aspirator bottle approximately 300 cc and 2⅝ inches diameter fitted with a rubber tube connection at bottom.

Three feet of rubber tubing, internal diameter 3/16 inch and external diameter 7/16 inch.

Ring stand approximately 4 feet high.

The test shall be carried out as follows :—

Open the stopcock of the burette, and place the aspirator bottle in the upper support. The bottle shall contain sufficient water, and the upper support shall be so adjusted that when the surface of the water in the burette coincides with the zero mark the depth of the water in the bottle is about one inch.

A strip of paper 2¼ inches wide shall be cut from the roll or sheet. The length of the strip shall be equal to the full width of the roll or sheet. The strip of paper shall be clamped between the rubber-faced metal discs, the stopcock closed and the bottle lowered until the surface of the water is 24 inches below the zero mark of the burette. The stopcock shall then be opened and allowed to remain open until 100 $cm^3$ of water have flowed out of the burette. The time required for the discharge of 100 $cm^3$ of water shall be measured by means of a stop watch or other suitable instrument.

The porosity number of the paper shall be the reciprocal of the number of seconds required for the discharge of the water multiplied by 100.

The porosity of the paper shall be measured at 10 points, 5 inches apart, located across the width of the roll or sheet.

The maximum, minimum and mean values of the porosity number shall be stated.

When the width of the roll or sheet is insufficient to enable 10 tests to be made on one strip, two or more strips shall be tested.

For the method of determining the direction of " length " and " width " of paper when supplied in sheets, see Appendix.

### 8. Absorption : Floating Test.

The paper shall be conditioned in accordance with Clause 1 before the absorption test is carried out.

The absorption of the paper shall be determined on samples 3 inches square by means of the apparatus shown in Fig. 3 and described below.

A is a cylindrical brass vessel 1 inch in internal diameter, connected to the funnel B through the tap C. The cylinder is surrounded by a water bath for temperature control, and for carrying out the test the whole is placed over a bunsen burner.

To carry out a test, oil is introduced into the funnel until a meniscus is formed above the upper edge of the cylinder A. Square samples of paper and a piece of plate glass ¼ inch thick and 2 inches square are laid over the upper end of A. The time that elapses up to the whole of the paper surface, as seen through the glass square, becoming impregnated shall be taken as a measure of the absorption of the sample.

The temperature of the water bath shall be 40° C. (104° F.), and pure Rape oil having a viscosity of 0·55 poise at this temperature shall be used.

The absorption test shall be carried out on 10 specimens taken from positions 5 inches apart located across the width of the roll or sheet. When the width of the roll or sheet is insufficient to enable 10 specimens to be cut from one strip, two or more strips shall be tested.

As most papers have two values for absorption depending upon the direction of flow of oil through the paper, tests shall be taken, first with one side downwards and then the other, and the average of the ten results for each recorded. The absorption number of the paper shall be the reciprocal of the mean of the average values for the two sides of the paper, multiplied by 100.

## CHEMICAL TESTS.

### 9. Moisture Loss on Drying at 100° C. (212° F.).

The paper shall be conditioned in accordance with Clause 1 before the test for moisture loss is carried out.

Approximately 25 grammes of the sample shall be weighed after conditioning, dried at a temperature of 100° C. (212° F.) for 3 hours and then re-weighed in an artificially dried atmosphere. The moisture loss shall be computed as a percentage of the weight of the sample after conditioning and before drying.

*Note.*—The paper should not be regarded as absolutely dry after being heated at 100° C. (212° F.).

### 10. Tests for Acidity and Alkalinity.

The tests for acidity and alkalinity shall be carried out on the paper as received, without artificial conditioning or drying. The amount of acid or alkali shall be computed on the bone-dry paper.

The tests for acidity and alkalinity shall be carried out as follows :—

Cut up 30 to 40 grammes of the paper into small pieces, weigh off duplicate lots of 10 grammes each, introduce each into a ¼ litre conical flask together with about 200 $cm^3$ of distilled water. Boil in a reflux condenser for two hours, decant the solution through a perforated disc, wash the paper residue twice with 75 $cm^3$ of warm water. Titrate the filtrate, using methyl orange indicator.

If the indicator shows the solution to be acid, estimate the amount by titration with a standard centinormal solution (N/100) of sodium hydrate ($NaOH$) or potassium hydrate ($KOH$). From the number of cubic centimetres of the reagent used the amount of acid is estimated.

If the indicator shows the solution to be alkaline, titrate with a standard centinormal solution (N/100) of sulphuric acid ($H_2SO_4$). From the number of cubic centimetres of the reagent used the amount of alkali is estimated.

In each case the number of cubic centimetres of the reagent required to neutralize the paper shall be stated.

### 11. Mineral Ash Test.

About 5 grammes of the dry sample obtained from the determination of moisture test shall be very completely ignited with all precautions against loss. The residue of incombustible mineral matter (ash) shall be weighed, and the amount computed as a percentage of the weight of the dried sample.

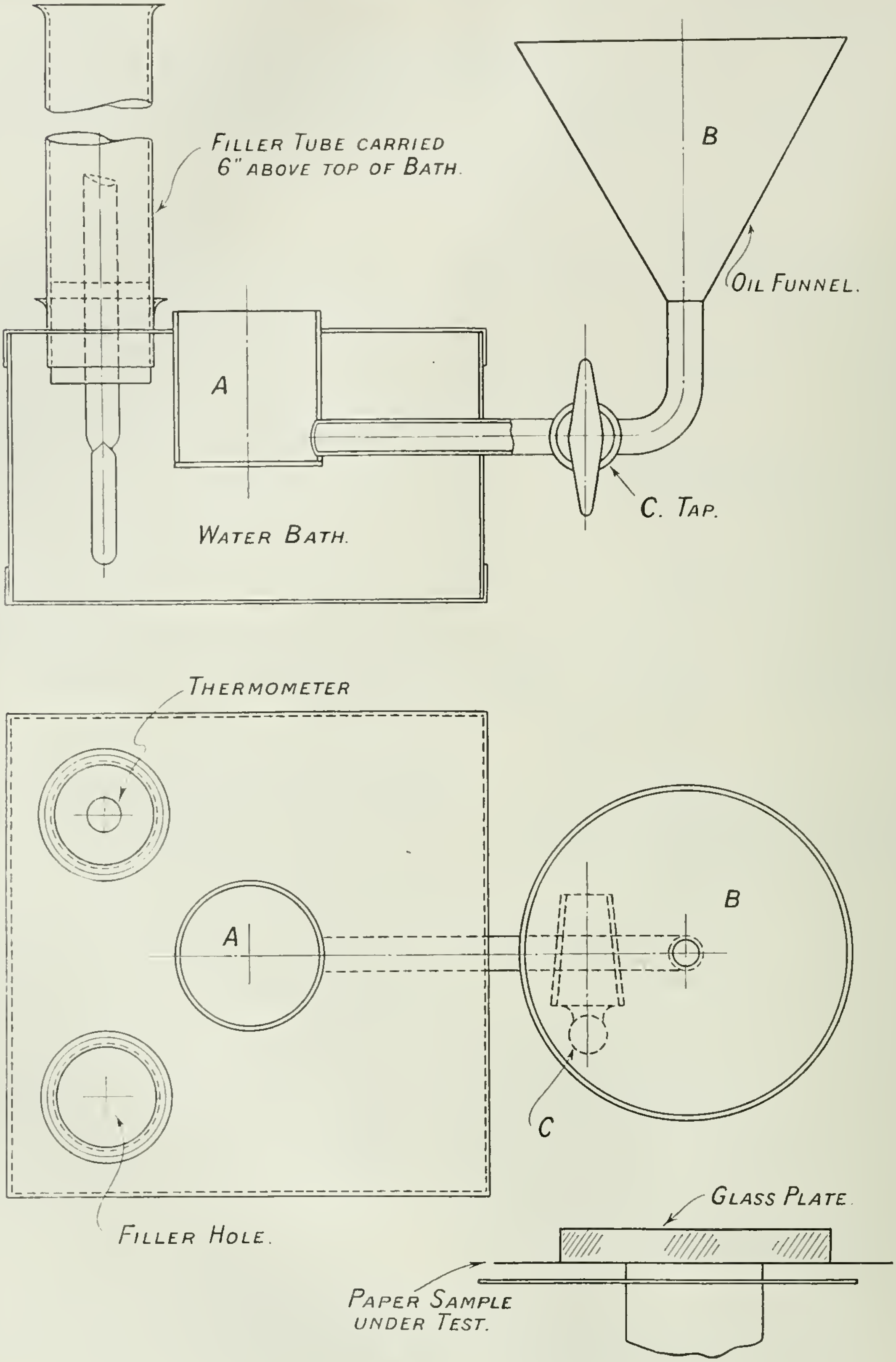


FIG. 3.—Apparatus for Measuring the Absorption of Paper.

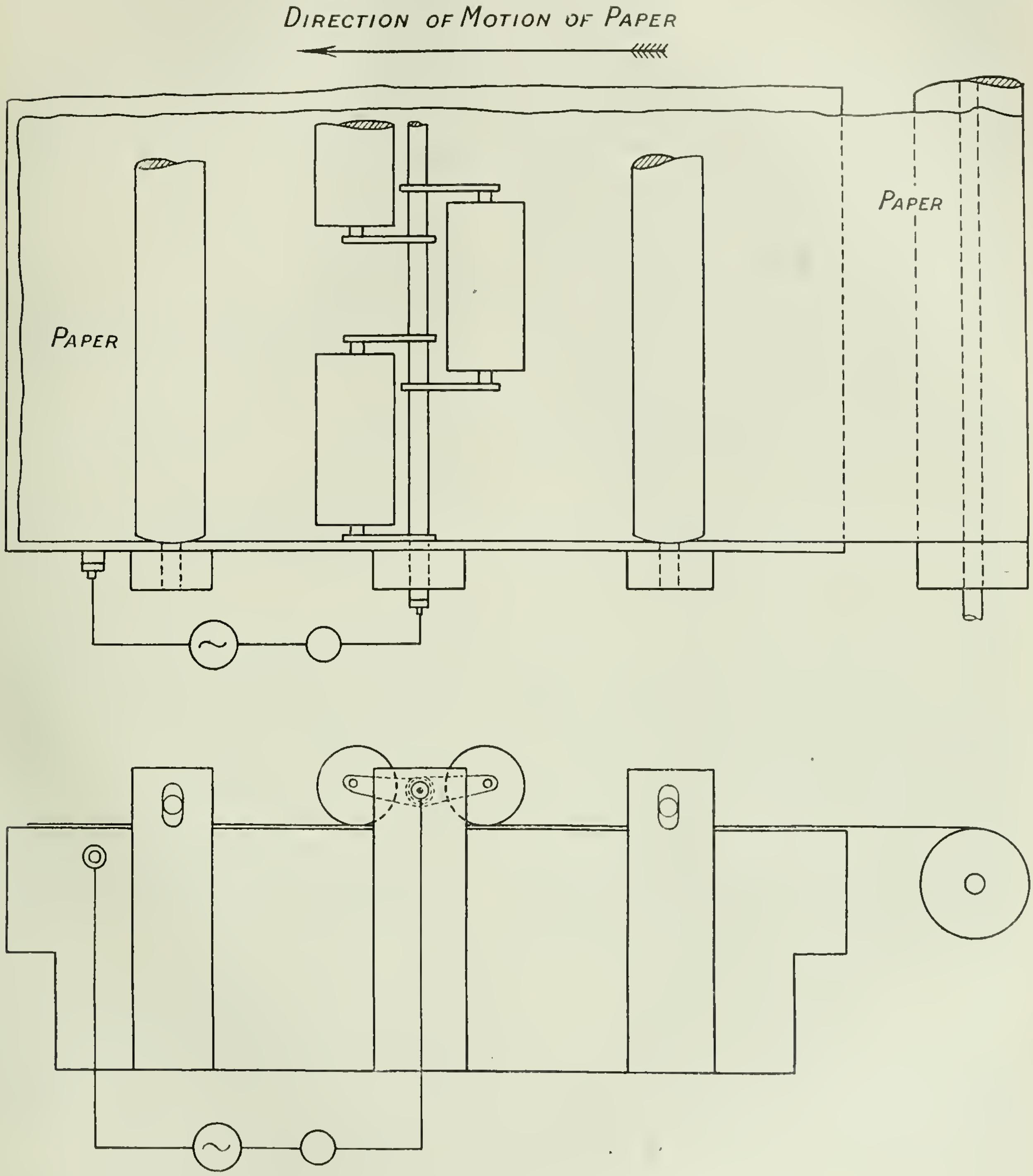


FIG. 4.—Apparatus for Flash Test for Conducting Particles.

### 12. Test for Resinous Material.

The test for resinous material shall be carried out on the paper as received, without artificial conditioning or drying. The amount of resinous material shall be computed on the bone-dry paper.

The total resinous material shall be determined as follows :—

Five grammes of the paper shall be cut into strips about ½ inch wide and folded into numerous small cross-wise folds. The strips shall be placed with 500 cm$^3$ of acidulated alcohol (450 cm$^3$ of 95 per cent alcohol, 45 cm$^3$ of distilled water and 5 cm$^3$ of glacial acetic acid) in a litre flask fitted with a reflux condenser, and the contents heated on a water bath for not less than two hours. The alcohol shall then be poured off, and the paper residue washed with acidulated alcohol twice, the washings being added to the main bulk.

The extract shall be poured into a weighed glass dish and the flask washed out with a small portion of the acidulated alcohol, which is added to the original extract. The alcohol shall then be evaporated, and just before the extracted total resins in the glass evaporating dish go to dryness, they shall be cooled, taken up with 25 cm$^3$ of ether, and transferred to a 250 cm$^3$ separatory funnel containing 100 cm$^3$ of distilled water and 25 cm$^3$ of a saturated solution of sodium chloride, the latter being present to prevent the formation of an emulsion. The funnel shall be shaken thoroughly and the contents allowed to separate. The water shall be drawn off into a second separatory funnel, and washed again with 25 cm$^3$ of ether.

The two ether extracts shall be combined and washed two or three times with 100 cm$^3$ of distilled water to remove all the salt and foreign matter other than ether-soluble resins. Should glue, which is extracted from the paper by the alcohol, interfere by emulsifying with the ether it may be removed readily by adding a strong solution of sodium chloride to the combined ether extracts, shaking thoroughly and draining it off, repeating, if necessary, before washing with distilled water. The washed extract shall be transferred to a weighed glass dish, evaporated to dryness slowly, dried in an oven at 95° C. (203° F.) to 100° C. (212° F.) for one half-hour, cooled and weighed. The increase in weight of the dish divided by 5 and multiplied by 100 will give the percentage of the total resinous material.

### 13. Test for Nitrogenous Material (Glue and Casein).

The tests for nitrogenous material shall be carried out on the paper as received, without artificial conditioning or drying. The amount of nitrogenous material shall be computed on the bone-dry paper.

The total nitrogenous material shall be determined by the Kjeldahl-Gunning method described in *Atack's Chemists' Year-Book*, 1921 edition, page 130, as follows :—

"About 1 gm of the paper is cautiously treated in a long-necked resistance flask with about 20 cc of conc. sulphuric acid (excessive frothing must be avoided). The heating is continued until the frothing subsides and then the flask is allowed to cool. (The nitrogen has been converted into ammonium sulphate.) Ten gm of potassium sulphate and a crystal of copper sulphate are added and the flask again heated until the contents are of a pale-green colour. Cool and dilute with 500 cc of distilled water.

One hundred cc of 30 per cent caustic soda are carefully poured down the side of the flask, avoiding mixing with the acid. The flask is connected with the acid absorption apparatus, the contents of the flask shaken up and the liberated ammonia distilled into excess N/10 acid. This is back titrated with N/10 caustic soda and the ammonia titration calculated to nitrogen.

A blank test must be carried out."

If no casein be present the percentage of nitrogen obtained multiplied by 5·6 will give the percentage of glue in the sample of paper.

> *Note.*—This test is of no value for the determination of the percentage of glue when glue and casein are present, since both contain nitrogen.

### 14. Chemical Tests for Metallic Particles.

The following test shall be carried out on a sample of paper, not less than one foot square, from every roll, or on a sheet from each ream.

The sample of paper shall be dipped into a 1 per cent solution (by volume) of acetic acid, and then allowed to air-dry for 1 hour while lying flat on a cloth.

When dry, the sample shall be dipped again in a solution containing 0·1 cm$^3$ acetic acid and 0·1 gramme of potassium ferricyanide in 100 cm$^3$ distilled water.

Each metallic iron particle will produce a blue spot on the paper, and each copper, brass or gun-metal particle a red spot.

The number of blue and red spots, respectively, per square foot of the paper shall be stated.

> *Note.*—The potassium ferricyanide solution should be tested before use with some precipitated ferric hydroxide dissolved in strong nitric acid, and diluted with water. The potassium ferricyanide solution should give no blue precipitate or coloration.

### 15. Flash Test for Conducting Particles.

It is not necessary to condition the paper prior to carrying out this test, provided the paper has been stored so as to attain the condition of ordinary room humidity.

The paper shall be drawn at a speed of 2 feet per minute between a metallic plate and a system of overlapping rollers, arranged as shown in Fig. 4.

The rollers shall be of brass, 3 inches long and ⅞ inch diameter. The edges of the rollers shall be rounded to a radius of 1/32 inch. Each roller shall exert a pressure of approximately 10 oz. on the paper under test.

The paper shall be subjected to an alternating potential difference of 50 volts (R.M.S.) per mil thickness of the paper. The frequency of the potential difference shall be 50 ∼ per second. A resistance shall be inserted in the testing circuit to limit the current so that the electrodes are not damaged when a puncture occurs. An electric lamp or other suitable indicator shall be used to demonstrate failure of the insulation.

On a failure occurring the defective spot shall be marked and the paper then drawn back and passed through a second time. The ability of the part originally defective to pass test on second application shall be noted.

Not less than 5 square feet of paper shall be tested. The number of punctures per square foot shall be stated.

### 16. Microscopical Examination.

A microscopical examination of the paper shall be carried out for the purpose of identifying the fibrous materials from which it has been made. The approximate percentage of the constituent fibres shall be stated.

The following method of preparing the samples for microscopical examination and the means of identification of the fibres are recommended by the U.S. Bureau of Standards.[*]

"Ten specimens, each about the size of a sixpence shall be cut from separate sheets, when the paper is submitted in sheets, or from different positions in the length of the roll, when the paper is submitted in a roll. The 10 specimens shall be torn into small pieces and placed in a 50 cc beaker to which approximately 20 cc of a 0·5 per cent solution of caustic soda is added.

The beaker is placed on a hot plate or stove and brought to a boil, but the boiling is not continued for more than a minute or two. The liquor is drained off and the pieces of paper are washed several times with tap water, care being taken that none is lost. They are then washed with approximately 20 cc of 0·5 per cent solution of hydrochloric acid, and then washed twice more with tap water. A portion of the small pieces is rolled between the fingers into a pill about the size of a small pea and transferred to a test tube, which is half filled with water. The test tube is shaken until the paper is disintegrated into fibres. By means of a glass tube of about 5 mm internal diameter a representative amount of the fibres is transferred to a glass slide and the water removed by placing several thicknesses of hard filter paper on either side of the slide. After the excess water has been thus removed, a strip of filter paper is placed on the fibres to absorb any traces, leaving the fibres dry, but not so dry that there will be difficulty in separating them. Two or three drops of the zinc-chloride-iodine stain described below are placed on the fibres, which are teased out with steel needles until the fibres are reasonably uniformly distributed and free from knots of fibres.

### *Composition and Preparation of Zinc-Chloride-Iodine Stain.*[*]

25 cc saturated zinc chloride solution at 70° F. (21·1° C.).
5·25 gm potassium iodide.
0·25 gm iodine.
12·5 gm distilled water.

The last three ingredients are mixed together and the zinc chloride added. The insoluble matter is allowed to settle at least overnight and the supernatant liquid decanted off. The stain must be kept in the dark or in a bottle opaque to light. It may be made up in larger quantities provided it is kept from the light and air.

After the fibres are properly teased out with the needles, another but thinner glass slide is placed on top of the first slide, and the excess stain is squeezed out and absorbed by blotting-paper. The slide is now ready for the microscope. (A magnification of about 50 diameters is usually found convenient.) Care must be observed to keep the slide away from the light before using it for the estimation, and in any case the estimation should be made at least within one hour from the time the slide was made up. Under the microscope, using the zinc-chloride-iodine stain, the fibres appear coloured as follows:—

| | |
|---|---|
| Cotton and linen rags<br>Cooked and bleached manilla | Wine red |
| Cooked and bleached wood-pulp<br>Cooked and bleached straw and esparto | Blue to blue violet |
| Mechanical or ground wood-pulp<br>Jute, uncooked, and manilla<br>Highly lignified fibres | Yellow to lemon yellow |

In making the estimation both the distinctive shape and markings of the fibres, as well as the colours as developed by the zinc-chloride-iodine stain, are of importance. Extreme care must be observed to have all beakers, test tubes, needles, and even fingers free from any fibrous material before beginning the preparation of a sample or slide."

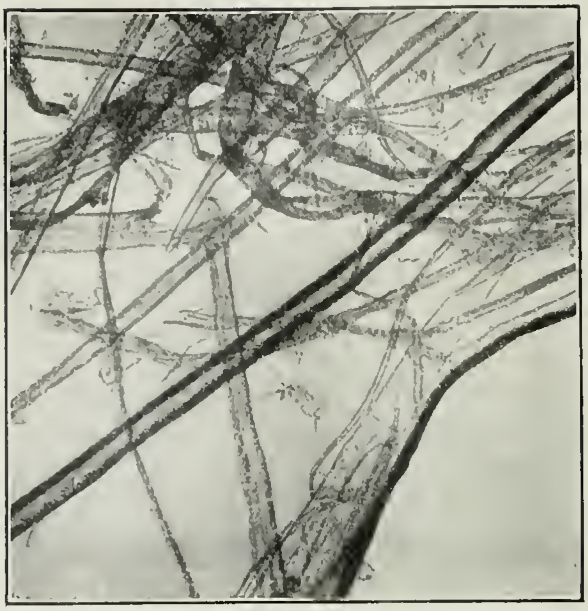
Reproductions of micro-photographs showing the fibres in papers containing the following materials are given for comparison:—

Fig. 5 (*a*) Manilla.
,, (*b*) Rag (cotton and linen).
,, (*c*) Jute.
,, (*d*) Chemical Wood-pulp.
,, (*e*) Mechanical Wood-pulp.
,, (*f*) "Paper mulberry" (*Broussonetia papyrifera*).

---

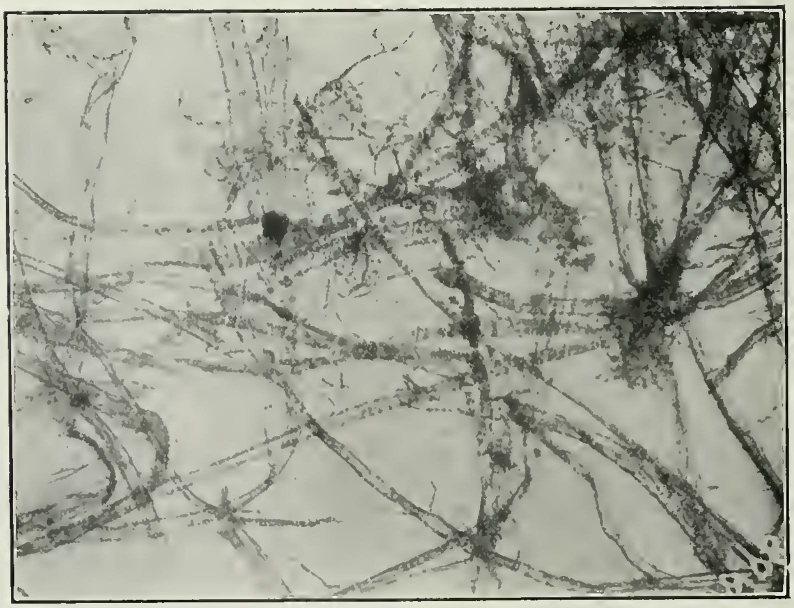
[*] Circular No. 107, "The Testing of Paper."

[*] This formula is tentative. Its value is subject to a number of factors that are now being studied by the Paper Section, Bureau of Standards, U.S.A.



( × 96)

FIG. 5.—(*a*) Manilla and Chemical Wood-pulp.



( × 96)

FIG. 5.—(*b*) Rag (Cotton and Linen).

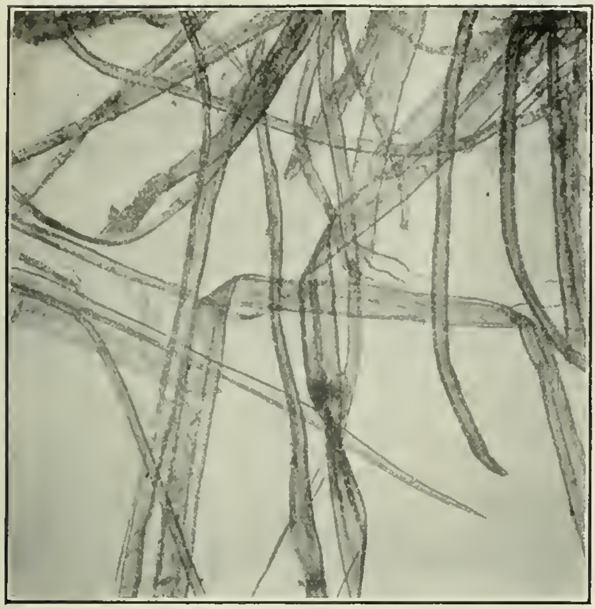

( × 96)

FIG. 5.—(*c*) Jute and Chemical Wood-pulp.

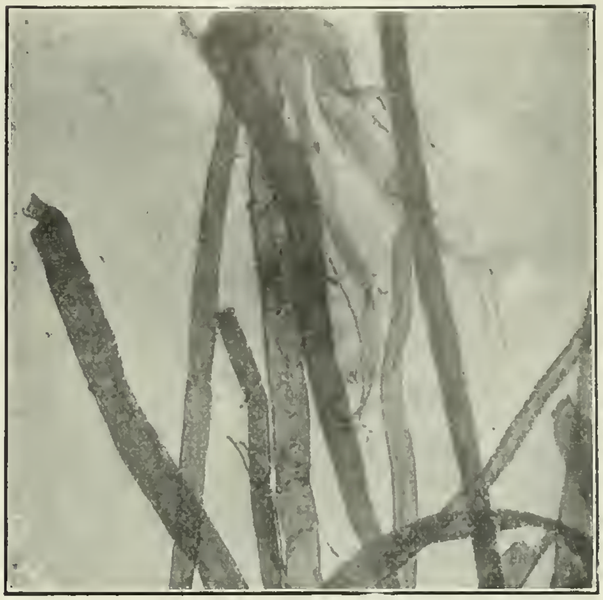

( × 96)

FIG. 5.—(*d*) Chemical Wood-pulp.

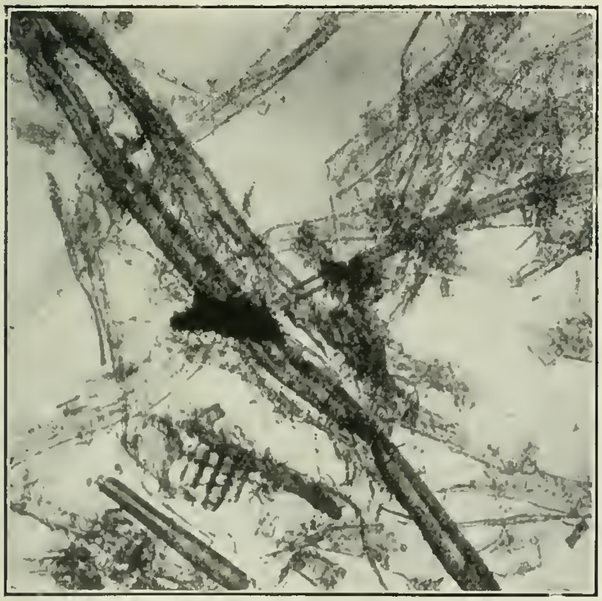

( × 96)

FIG. 5.—(*e*) Mechanical Wood-pulp.

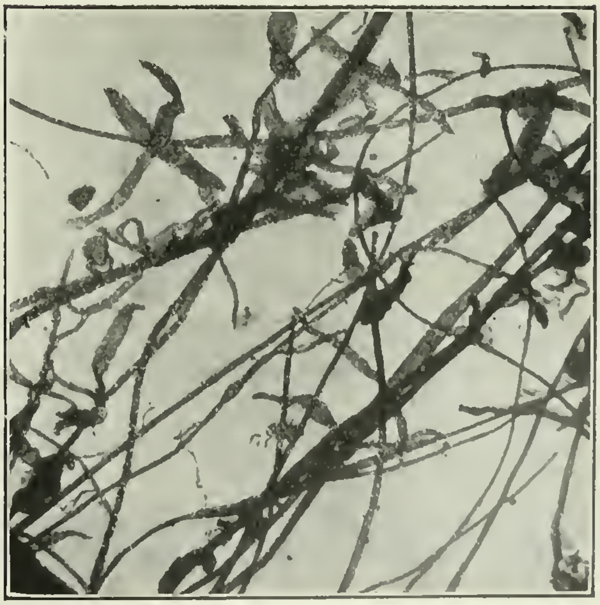

( × 96)

FIG. 5.—(*f*) "Paper Mulberry."

## IV. SCHEDULE OF USES AND TESTS.

A cross indicates that the test as described in the Specification shall be carried out.

| Class and Use | Tests | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Chemical Tests | | | | | | | |
| | Determination of Thickness | Determination of Density | Tensile Strength and Extension | Ageing | Tearing Strength | Porosity | Absorption | Moisture Loss on Drying | Acidity and Alkalinity | Mineral Ash | Resinous Material | Nitrogenous Material | Chemical Test for Metallic Particles | Flash Test for Conducting Particles | Microscopical Examination |
| *Class A.*<br>Manufacture of tubes and sheets<br>Between layers of windings and similar purposes<br>Insulating wrappings<br>Backing for mica folium, mica tape or micanite<br>Condensers | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| *Class B.*<br>Slot insulation<br>Wrapping core bolts<br>Bobbin flanges and other parts where high insulation is not required | X | — | X | X | X | X | X | X | X | — | — | — | X | X | — |
| *Class C.*<br>Core-plate insulation<br>Covering for micanite | X | — | — | — | X | — | — | — | — | — | — | — | — | — | — |

## APPENDIX.

### Method for Determining the Direction of "Length" and "Width" of Paper, for Use in Carrying out the Tests Specified in Clauses 4, 5, 6 and 7.

The direction of the "length" and "width" of the paper may be ascertained by the "Direction Test" as follows:—

Cut a disc of paper about 3 inches diameter and moisten one side. The paper will tend to curl to form a tube the axis of which is parallel to the machine direction of the paper.

# REPORT UPON TESTS ON HARD DRAWN COPPER WIRES AND CABLES FOR OVERHEAD TRANSMISSION LINES.

[Report (Ref. F/T5) received from the British Electrical and Allied Industries Research Association.]

### Contents.

| | Page |
|---|---|
| Introduction | 997 |
| Scope of Investigation | 997 |
| Material under Test | 997 |
| Range of Samples Tested | 997 |
| Ultimate Tensile Strength | 998 |
| Extension on Fracture | 998 |
| Limit of Proportionality | 999 |
| Modulus of Elasticity | 999 |
| Twist and Wrap Tests | 999 |
| Results of Tests | 999 |
| I. Mechanical Tests on Single Wires supplied separately | 999 |
| II. Mechanical Tests on Short Stranded Cables | 1005 |
| III. Mechanical Tests on Long Stranded Cables | 1008 |
| IV. Pitch and Lay of Constituent Wires of Long Stranded Cables | 1012 |
| V. Conductivity Tests on Single Wires supplied separately | 1012 |

### Introduction.

The British Engineering Standards Association is drafting Standard Specifications for Conductors for use on Overhead Transmission Lines. It is desired to specify the ultimate strength and the extension of single wires and stranded cables, and also the limit of proportionality and the modulus of elasticity.

The Electrical Research Association, at the request of the British Engineering Standards Association, has undertaken an investigation on hard drawn copper, steel and aluminium wires and cables to ascertain their physical properties. The tests have been carried out at the National Physical Laboratory.

The results are of considerable practical importance, many of the tests having been carried out for the first time on 100-yard lengths of cable under conditions approximating to those of actual use, a high degree of accuracy being obtained throughout.

This report deals with the results obtained on hard drawn copper wires and cables, both short and long lengths. The results obtained on aluminium and steel wires and cables will be the subject of later reports.

### Scope of Investigation.

The physical properties and tests to which special attention was directed were as follows:—

Ultimate tensile strength.
Extension on fracture.
Limit of proportionality.
Modulus of elasticity.
Twist and wrap tests.

### Material under Test.

The material on which the tests, dealt with in this report, were carried out consisted of hard drawn copper as furnished for overhead line construction. Single wires (see Table 1A) were obtained at the same time as the cables (see Table 1B) and purported to be of the same material. This was not borne out in one or two instances by the results obtained. For the purpose of determining the efficiency of the cables a comparison was therefore made also with tests on single wires taken from the individual cables (see Table 10).

Table 1A.

*Single Wires supplied separately.*

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch |
|---|---|---|
| AKL | A | 0·104 |
| | | 0·136 |
| | | 0·144 |
| | | 0·166 |
| | | 0·185 |
| | | 0·215 |
| AKN | B | 0·104 |
| | | 0·136 |
| | | 0·144 |
| | | 0·166 |
| | | 0·185 |
| | | 0·215 |
| AKO | C | 0·104 |
| | | 0·136 |
| | | 0·144 |
| | | 0·166 |
| | | 0·185 |
| | | 0·215 |

### Range of Samples Tested.

Tests were carried out on single wires of diameters ranging from 0·104 inch to 0·215 inch, and on stranded cables consisting of 3, 7, 19 and 37 wires respectively, the diameters of the wires ranging from 0·144 inch to 0·215 inch.

(*a*) *Single wires supplied separately* (see Table 1A).

Tests were carried out on short lengths (10 inches) of single wires. The tests show close agreement between the behaviour of short lengths of wire and of long lengths of cable.

The prevailing practice of determining the physical properties of single wires by tests on short specimens is regarded as satisfactory.

TABLE 1B.

*Stranded Cables.*

| N.P.L. Mark | Maker | Type |
|---|---|---|
| AKL4A | A | 3/·166 |
| AKL4B | | 7/·166 |
| AKL4C | | 7/·215 |
| AKL4D | | 19/·144 |
| AKL4E | | 19/·166 |
| AKL4F | | 37/·144 |
| AKN4A | B | 3/·166 |
| AKN4B | | 7/·166 |
| AKN4C | | 7/·215 |
| AKN4D | | 19/·144 |
| AKN4E | | 19/·166 |
| AKN4F | | 37/·144 |
| AKO4A | C | 3/·166 |

(*b*) *Stranded cables* (see Table 1B).

The tests on short lengths of cable give results which are different from those of tests on long lengths of cable, except in so far as they refer to ultimate strength, and on the single wires of which the cables are composed. In short lengths of cable subjected to tension it is apparent that the stress is not shared equally between the wires. The results of tests on short lengths of cable must be rejected on this account, with the exception of the ultimate strength tests.

The tests on long lengths of cables are consistent with one another and (important to note) with tests on the individual straightened wires supplied separately (see Table 12).

### ULTIMATE TENSILE STRENGTH.

The ultimate tensile strengths of the various single wires tested are in close agreement. With one exception the breaking stress exceeds 24 tons per square inch.

The figure of 24 tons per square inch is recommended for adoption as a minimum value for the sizes of wire tested.

The breaking stress of the cables was found to be less than that of their constituent wires; this could be accounted for by the assumption of unequal loading of the individual wires.

The strength of a cable in terms of the sum of the strengths of the individual constituent wires was found to vary as follows:—

| | |
|---|---|
| 3 wires.. .. .. | 96 per cent |
| 7 ,, .. .. .. | 95 ,, |
| 19 ,, .. .. .. | 93 ,, |
| 37 ,, .. .. .. | 93 ,, |

The number of tests carried out was not sufficient to establish the relationship between percentage strength and number of wires.

It is recommended that the reduction of strength indicated above should be taken into account where cables are used.

### EXTENSION ON FRACTURE.

The percentage extension on fracture varies with the length of wire tested, and if elongation is to be specified the length of the test specimen must be stated.

The tests show that the percentage extension on fracture varies with the diameter of the wire and with the ultimate tensile strength; the relationship is not very definite. Previous tests on single wires have shown a fairly definite relationship between diameter of wire and ultimate stress of the form:—

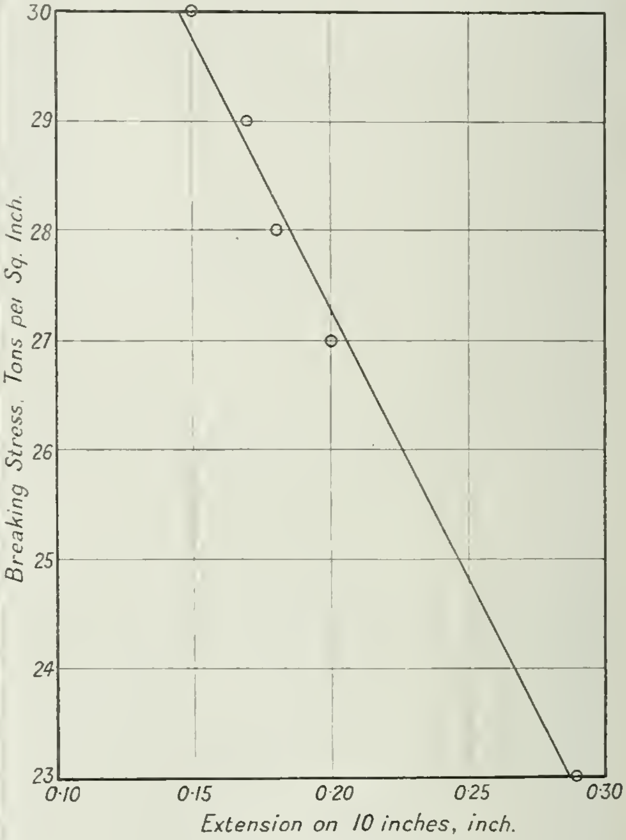


FIG. 1.—Grouped Results of Extension Tests on Single Wires supplied separately.

$$\text{Stress} = A - B \times \text{diameter of wire.}$$

The present tests whilst showing generally a lower breaking stress in the larger wires are irregular in this respect.

The present tests show a considerable variation from such a relationship.

If the results of the tests recorded in Table 3 be grouped in the order of ultimate stress, the values of extension as stated are obtained. The grouped results are shown in Fig. 1.

It appears, therefore, that the specification of a minimum ultimate stress and a minimum elongation on fracture will closely define the quality of the wire.

A minimum stress of 24 tons per square inch and a minimum extension of 0·15 in. in 10 in. or 0·08 in. in 2 in. are recommended.

| Ultimate Stress, tons per sq. in. | Extension on 10 inches |
|---|---|
| Over 30 | 0·15 inch |
| 29–30 | 0·17 ,, |
| 28–29 | 0·18 ,, |
| 27–28 | 0·2 ,, |
| 26–27 | 0·22 ,, |
| 23 | 0·29 ,, |

### LIMIT OF PROPORTIONALITY.

The limit of proportionality between stress and strain is not a physical constant and should therefore have no place in a specification for the material of a wire.

It is advisable, however, that the working stress of overhead wires shall be determined with due regard to the degree of proportionality.

The tests show that the limit of proportionality, though at first much lower than the generally recognized values, increases with repeated loadings. The limits given in Table 12 are those found on a first loading, and in view of the characteristic increase of the limit on repeated loading should not be taken as a basis for deciding the maximum working stress of an overhead wire.

The limit of proportionality corresponding to the higher values of the modulus of elasticity after repeated loadings is not given in the tests. In view of the results of the tests it is thought that the practical limit may with safety be assumed to exceed 50 per cent of the ultimate stress.

### MODULUS OF ELASTICITY.

The effect of repeated loading to a point beyond the limit of proportionality is to increase the apparent modulus.

On repeated loading the apparent modulus increases towards a maximum value which is the true modulus of the material.

It appears that for single wires and for stranded cables of from 3 to 19 wires a modulus of $18 \times 10^6$ lb. per sq. in. may be regarded as a fair value.

The tests on the 37-wire strand show a lower value of the modulus. It should be noted, however, that with this size of cable, the maximum load applied was below the primitive limit of proportionality of the cable. If repeated loadings above this limit had been applied it is probable that a higher value would have been obtained.

A practical point arises from the fact that the true modulus of the material is higher than the value obtained on the first loading. In traction and transmission line work it has been suggested that it would be desirable if the wires and cables could have the *true value* of the modulus when *first erected.* If the repeated loadings were applied in the wire-maker's works before coiling on to drums, uncertainty would exist as to the effect of coiling and uncoiling on the final value of the modulus when the wire was strung up on site. Further elongation tests would be necessary to ascertain whether the coiling and uncoiling reduced the modulus from the *true value.**

### TWIST AND WRAP TESTS.

The results of these tests show no direct relationship to the percentage elongation referred to above. The tests are of interest, but there is not sufficient evidence to show that the specification of such tests is of more than general value.

TABLE 2.

*Dimensions of Coils of Single Wire as supplied.*

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Diameter of Coil as received | |
|---|---|---|---|---|
| | | | Internal, inches | External, inches |
| AKL | A | 0·104 | 16·5 | 19·5 |
| | | 0·136 | 16·5 | 20·0 |
| | | 0·144 | 16·5 | 20·0 |
| | | 0·166 | 16·5 | 20·5 |
| | | 0·185 | 16·5 | 20·5 |
| | | 0·215 | 16·5 | 21·0 |
| AKN | B | 0·104 | 20·0 | 22·5 |
| | | 0·136 | 19·5 | 22·5 |
| | | 0·144 | 19·0 | 22·5 |
| | | 0·166 | 19·5 | 23·0 |
| | | 0·185 | 19·5 | 23·0 |
| | | 0·215 | 20·5 | 24·0 |
| AKO | C | 0·104 | 21·5 | 24·0 |
| | | 0·136 | 21·5 | 24·0 |
| | | 0·144 | 21·0 | 24·0 |
| | | 0·166 | 22·0 | 25·5 |
| | | 0·185 | 22·0 | 26·0 |
| | | 0·215 | 22·5 | 26·0 |

It should be borne in mind, however, that twist and wrap tests can be carried out so easily that wire-makers prefer these tests to extension tests.

## RESULTS OF TESTS.

Details of the methods of test and the results obtained at the N.P.L. are given on the following pages.†

### I. MECHANICAL TESTS ON SINGLE WIRES SUPPLIED SEPARATELY.

The samples of single wire were supplied in the form of coils, the dimensions of which are given in Table 2.

---

* The wire-makers on the Sub-Committee have stated that it would be impracticable to carry out the repeated loadings at the manufacturer's works.

† The original Report was accompanied by drawings showing the apparatus used. These can be inspected at the E.R.A. office.

### DETERMINATION OF BREAKING LOAD.

The tensile strength tests were carried out in accordance with the British Engineering Standards Association Specification for Hard Drawn Copper Wire, viz. 9/10 of the breaking load was applied in five seconds and the remaining 1/10 in five seconds. In all cases the air temperature was about 22° C.

The results of these tests in general on three samples of each wire are given in Table 3. All the test pieces from each coil were cut from the sample end, and were not straightened before test.

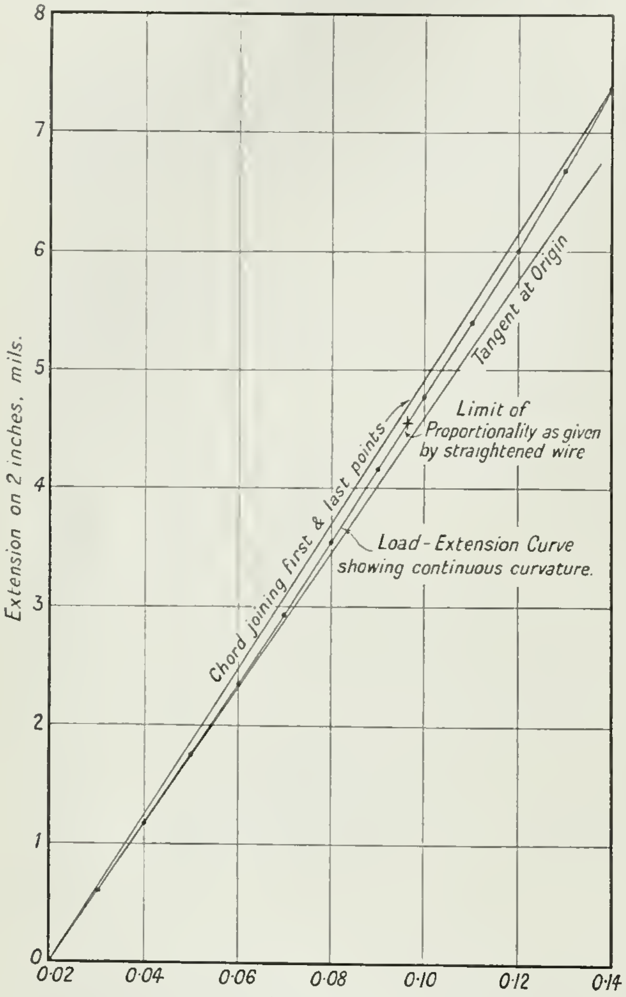


FIG 2.—Load-Extension Curves of Unstraightened Single Wires supplied separately (Specimen AKN1A6).

### DETERMINATION OF THE LIMIT OF PROPORTIONALITY, MODULUS, AND EXTENSION.

Tensile tests were made on straightened lengths of wire having 10 in. between the grips. The extension on a 2-in. middle portion of the wire was measured by means of a Marten's mirror extensometer. The primitive limit of proportionality and the modulus at first loading were obtained by loading up in steps to a point just beyond the limit of proportionality. The load was then removed, and a second modulus obtained by again loading up to the same point.

The results are given in Table 4.

It was found that a straight elastic line, and, therefore, the limit of proportionality, could not be obtained by tests made on bent wires, so that all the wires had to be straightened before test. Fig. 2, giving results of a test on an unstraightened wire, illustrates this point. Fig. 3 gives the results of typical tests on wires previously straightened.

It will be noted that the values of the limit of proportionality are much lower than the generally recognized values. They are the loads or stresses at which the first deviations from Hooke's Law were observed upon the first loading of the wires. The values of these limits of proportionality depend, to a large extent, upon the accuracy with which the strains can be observed, and it may be assumed that, in general, the lower the accuracy the higher will be the value of the apparent limit of proportionality.

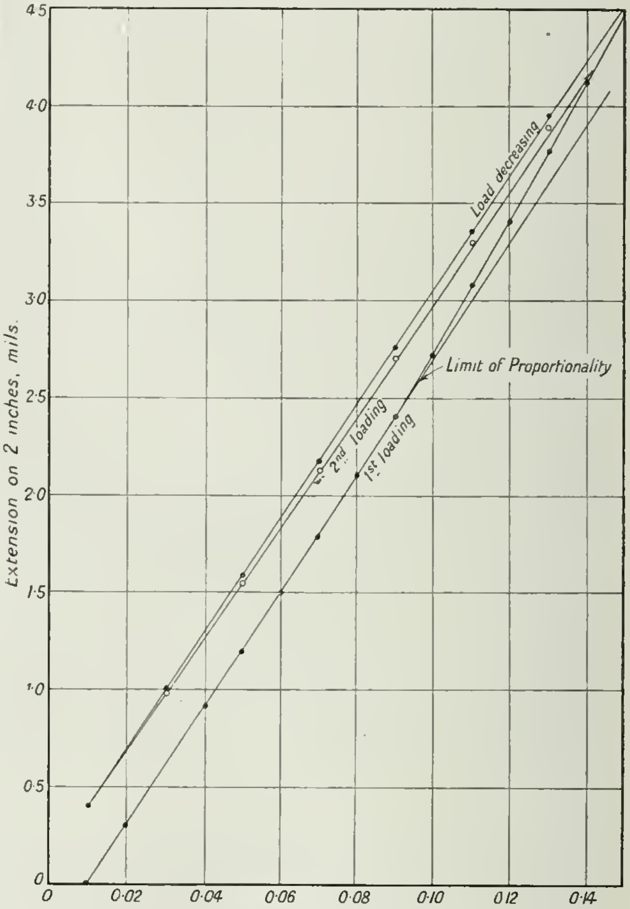


FIG. 3.—Typical Load-Extension Curves of Straightened Single Wires supplied separately.

The values in the B.E.S.A. Report No. 55 were obtained from autographic stress/strain records in which the total extensions of a 50-ft. length of wire

TABLE 3.

*Tensile Strength and Extension of Single Wires supplied separately* (see Table 1A).

| N.P.L. Mark | Maker | Diameter of Wire, inch | Cross-sectional Area of Wire, sq. in. | Breaking Load, tons | Ultimate Stress, tons per sq. inch | Extension on | |
|---|---|---|---|---|---|---|---|
| | | | | | | 10 inches | 2 inches |
| | | | | | | inch | inch |
| AKL1A | A | 0·104 | 0·0085 | 0·2540 | 29·9 | 0·11 | 0·05 |
| | | | | 0·2610 | 30·7 | 0·12 | 0·07 |
| | | | | 0·2585 | 30·4 | 0·14 | 0·07 |
| AKL1B | A | 0·1365 | 0·0146 | 0·4185 | 28·7 | 0·175 | 0·085 |
| | | | | 0·4200 | 28·8 | 0·14 | 0·08 |
| | | | | 0·4180 | 28·6 | 0·17 | 0·09 |
| AKL1C | A | 0·1445 | 0·0164 | 0·4655 | 28·4 | 0·18 | 0·10 |
| | | | | 0·4665 | 28·4 | 0·18 | 0·11 |
| | | | | 0·4635 | 28·3 | 0·17 | 0·11 |
| AKL1D | A | 0·1665 | 0·02175 | 0·5850 | 26·9 | 0·225 | 0·12 |
| | | | | 0·5895 | 27·1 | 0·23 | 0·13 |
| | | | | 0·5840 | 26·8 | 0·18 | 0·115 |
| AKL1E | A | 0·1855 | 0·0275 | 0·7045 | 26·1 | 0·22 | 0·13 |
| | | | | 0·7100 | 26·3 | 0·25 | 0·14 |
| | | | | 0·7105 | 26·3 | 0·25 | 0·13 |
| AKL1F | A | 0·215 | 0·0363 | 0·8445 | 23·3 | 0·29 | 0·17 |
| | | | | 0·8540 | 23·5 | 0·31 | 0·17 |
| | | | | 0·8510 | 23·4 | 0·28 | 0·14 |
| AKN1A | B | 0·104 | 0·0085 | 0·2475 | 29·1 | 0·13 | 0·05 |
| | | | | 0·2475 | 29·1 | 0·13 | 0·06 |
| | | | | 0·2455 | 28·9 | 0·15 | 0·07 |
| AKN1B | B | 0·136 | 0·0145 | 0·4110 | 28·3 | 0·13 | 0·07 |
| | | | | 0·4135 | 28·5 | 0·13 | 0·07 |
| | | | | 0·4125 | 28·45 | 0·13 | 0·08 |
| AKN1C | B | 0·143 | 0·0161 | 0·4455 | 27·7 | 0·13 | 0·07 |
| | | | | 0·4515 | 28·0 | 0·16 | 0·085 |
| | | | | 0·4500 | 28·0 | 0·13 | 0·09 |
| AKN1D | B | 0·1655 | 0·0215 | 0·5845 | 27·2 | 0·17 | 0·08 |
| | | | | 0·5905 | 27·5 | 0·18 | 0·09 |
| | | | | 0·5900 | 27·4 | 0·17 | 0·09 |
| AKN1E | B | 0·1845 | 0·0267 | 0·7310 | 27·4 | 0·185 | 0·10 |
| | | | | 0·7230 | 27·1 | 0·18 | 0·10 |
| | | | | 0·7285 | 27·3 | 0·17 | 0·09 |
| AKN1F | B | 0·215 | 0·0363 | 0·9835 | 27·1 | 0·185 | 0·10 |
| | | | | 0·9870 | 27·2 | 0·195 | 0·10 |
| | | | | 0·9745 | 26·8 | 0·21 | 0·105 |
| AKO1A | C | 0·104 | 0·0085 | 0·2505 | 29·5 | 0·16 | 0·07 |
| | | | | 0·2580 | 30·3 | 0·20 | 0·08 |
| | | | | 0·2500 | 29·4 | 0·275 | 0·115 |
| AKO1B | C | 0·136 | 0·0145 | 0·4165 | 28·7 | 0·20 | 0·09 |
| | | | | 0·4040 | 27·9 | 0·165 | 0·10 |
| | | | | 0·4175 | 28·8 | 0·23 | 0·10 |
| AKO1C | C | 0·144 | 0·0163 | 0·4690 | 28·8 | 0·17 | 0·095 |
| | | | | 0·4765 | 29·2 | 0·22 | 0·105 |
| | | | | 0·4750 | 29·1 | 0·17 | 0·095 |
| AKO1D | C | 0·166 | 0·0216 | 0·6050 | 28·0 | 0·26 | 0·14 |
| | | | | 0·6050 | 28·0 | 0·28 | 0·12 |
| | | | | 0·6010 | 27·8 | 0·25 | 0·115 |
| AKO1E | C | 0·184 | 0·0266 | 0·7320 | 27·5 | 0·20 | 0·12 |
| | | | | 0·7560 | 28·4 | 0·20 | 0·10 |
| | | | | 0·7520 | 28·3 | 0·235 | 0·125 |
| AKO1F | C | 0·215 | 0·0363 | 0·9915 | 27·3 | 0·23 | 0·13 |
| | | | | 0·9840 | 27·1 | 0·28 | 0·12 |
| | | | | 1·0085 | 27·8 | 0·27 | 0·12 |

occupied about 5 in. on the chart. The accuracy in the present tests was at least five times as great, and it is quite possible that if still greater refinement of the measuring apparatus can be obtained, a still lower value will be found.

The value of the primitive limit of proportionality is not of very great importance. If the wire is reloaded after the limit of proportionality has been exceeded a new and higher value of the limit is obtained, the amount of the increase depending on the amount by which the primitive limit of proportionality has been exceeded.

TABLE 4.

*Limits of Proportionality, Modulus and Extension of Single Wires supplied separately* (see Table 1A).

| | | | | | | |
|---|---|---|---|---|---|---|
| | N.P.L. mark, AKL<br>Maker, A | | | | | |
| Diameter of wire, inch .. .. .. | 0·1043 | 0·1363 | 0·1444 | 0·1665 | 0·1850 | 0·215 |
| Cross-sectional area of wire, square inch.. | 0·00854 | 0·01458 | 0·01638 | 0·02177 | 0·02688 | 0·03631 |
| Primitive limit of proportionality, ton .. | 0·093 | 0·093 | 0·102 | 0·116 | 0·190 | 0·146 |
| Primitive limit of proportionality, tons per square inch .. .. .. .. .. | 10·9 | 6·4 | 6·2 | 5·3 | 7·1 | 4·0 |
| Maximum load, ton .. .. .. .. | 0·2425 | 0·4005 | 0·4525 | 0·5665 | 0·6865 | 0·824 |
| Ultimate stress, tons per square inch .. | 28·4 | 27·5 | 27·6 | 26·0 | 25·5 | 22·7 |
| Modulus (1st), lb. per square inch × 10⁻⁶.. | 18·0 | 18·3 | 18·7 | 18·3 | 18·2 | 16·7 |
| Modulus (2nd), lb. per square inch × 10⁻⁶ | 18·7 | 18·9 | 19·6 | 18·5 | 18·3 | 17·0 |
| Extension on 10 in., inch .. .. .. | 0·10 | 0·12 | 0·14 | 0·13 | 0·19 | 0·19 |
| Extension on 2 in., inch .. .. .. | 0·06 | 0·07 | 0·09 | 0·09 | 0·13 | 0·14 |
| | N.P.L. mark, AKN<br>Maker, B | | | | | |
| Diameter of wire, inch .. .. .. | 0·1038 | 0·1363 | 0·1435 | 0·1657 | 0·185 | 0·215 |
| Cross-sectional area of wire, square inch .. | 0·00846 | 0·01458 | 0·01617 | 0·02156 | 0·02688 | 0·0361 |
| Primitive limit of proportionality, ton .. | 0·097 | 0·11 | 0·11 | 0·148 | 0·258 | 0·296 |
| Primitive limit of proportionality, tons per square inch .. .. .. .. .. | 11·5 | 7·5 | 6·8 | 6·9 | 9·6 | 8·2 |
| Maximum load, ton .. .. .. .. | 0·2395 | 0·4055 | 0·439 | 0·577 | 0·7153 | 0·9725 |
| Ultimate stress, tons per square inch .. | 28·3 | 27·8 | 27·2 | 26·8 | 26·6 | 26·8 |
| Modulus (1st), lb. per square inch × 10⁻⁶.. | 17·5 | 17·8 | 17·5 | 18·2 | 16·9 | 16·4 |
| Modulus (2nd), lb. per square inch × 10⁻⁶ | 18·4 | 18·2 | 18·1 | 18·8 | 17·0 | 17·2 |
| Extension on 10 in., inch .. .. .. | 0·10 | 0·10 | 0·11 | 0·13 | 0·17 | 0·20 |
| Extension on 2 in., inch .. .. .. | 0·06 | 0·07 | 0·07 | 0·09 | 0·09 | 0·11 |
| | N.P.L. mark, AKO<br>Maker, C | | | | | |
| Diameter of wire, inch .. .. .. | 0·1042 | 0·1359 | 0·144 | 0·1664 | 0·1837 | 0·215 |
| Cross-sectional area of wire, square inch .. | 0·00852 | 0·0145 | 0·01628 | 0·02175 | 0·0265 | 0·03631 |
| Primitive limit of proportionality, ton .. | 0·080 | 0·136 | 0·124 | 0·133 | 0·254 | 0·220 |
| Primitive limit of proportionality, tons per square inch .. .. .. .. .. | 9·4 | 9·4 | 7·6 | 6·1 | 9·6 | 6·1 |
| Maximum load, ton .. .. .. .. | 0·2405 | 0·407 | 0·460 | 0·5895 | 0·7385 | 0·978 |
| Ultimate stress, tons per square inch .. | 28·2 | 28·1 | 28·3 | 27·1 | 27·9 | 26·9 |
| Modulus (1st), lb. per square inch × 10⁻⁶.. | 18·4 | 18·4 | 18·2 | 18·3 | 17·8 | 17·8 |
| Modulus (2nd), lb. per square inch × 10⁻⁶ | 19·3 | 19·0 | 18·7 | 18·8 | 18·2 | 18·4 |
| Extension on 10 in., inch .. .. .. | 0·15 | 0·12 | 0·10 | 0·16 | 0·19 | 0·12 |
| Extension on 2 in., inch .. .. .. | 0·08 | 0·07 | 0·07 | 0·08 | 0·11 | 0·10 |

The maximum load was also obtained during these tests, and the results are given in Table 4. The final 1/10 of the load was applied in approximately two minutes, and the results are referred to subsequently as "slow loading" tests (see Tables 7 and 10).

### TWIST TESTS.

The twist tests were made in accordance with the British Engineering Standards Association Specification for hard drawn copper wire. The test piece was gripped in two jaws, one fixed in the fast headstock of a small lathe, and the other fixed in the loose headstock, but allowed to move axially. The lathe was made to rotate at 40 revolutions per minute until fracture occurred, and the number of twists was indicated by the spiral formed by a mark previously painted along the wire. All the wires were straightened before test, and were cu

### TABLE 5.

*Twist Tests on Single Wires supplied separately* (see Table 1A).

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Number of Twists on | | |
|---|---|---|---|---|---|
| | | | 6-in. Length | 6-in. Length (Repeat) | 3-in. Length |
| AKL2A | A | 0·104 | 49<br>43<br>50 | 45<br>24<br>46 | 30<br>29½<br>32 |
| AKL2B | A | 0·136 | 24½<br>36<br>30 | 25<br>34½<br>32 | 13½<br>13½<br>19 |
| AKL2C | A | 0·144 | 34½<br>31<br>30 | —<br>—<br>— | —<br>—<br>— |
| AKL2D | A | 0·166 | 32½<br>32½<br>28 | —<br>—<br>— | —<br>—<br>— |
| AKL2E | A | 0·185 | 23<br>22½<br>23½ | —<br>—<br>— | —<br>—<br>— |
| AKL2F | A | 0·215 | 27<br>24<br>23 | —<br>—<br>— | —<br>—<br>— |
| AKN2A | B | 0·104 | 77<br>81<br>81 | —<br>—<br>— | 43<br>44<br>45 |
| AKN2B | B | 0·136 | 60<br>61<br>54 | 59<br>59<br>58 | 33<br>32<br>32 |
| AKN2C | B | 0·144 | 52<br>51<br>54 | —<br>—<br>— | —<br>—<br>— |
| AKN2D | B | 0·166 | 50<br>49<br>49 | —<br>—<br>— | —<br>—<br>— |
| AKN2E | B | 0·185 | 36<br>35<br>37 | —<br>—<br>— | —<br>—<br>— |
| AKN2F | B | 0·215 | 37<br>36<br>37 | —<br>—<br>— | —<br>—<br>— |
| AKO2A | C | 0·104 | 58<br>65<br>73 | —<br>—<br>— | 38<br>40<br>39 |
| AKO2B | C | 0·136 | 52<br>40½<br>48 | 49½<br>44<br>47½ | 26<br>24<br>27 |
| AKO2C | C | 0·144 | 50<br>50<br>54 | —<br>—<br>— | —<br>—<br>— |
| AKO2D | C | 0·166 | 42<br>34<br>39 | —<br>—<br>— | —<br>—<br>— |
| AKO2E | C | 0·185 | 30½<br>33<br>34 | —<br>—<br>— | —<br>—<br>— |
| AKO2F | C | 0·215 | 21½<br>25<br>21 | —<br>—<br>— | —<br>—<br>— |

### TABLE 6.

*Wrap Tests on Single Wires supplied separately* (see Table 1A).

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Statement of Results |
|---|---|---|---|
| AKL3A | A | 0·104 | 9, 6, 6, 1<br>9, 6, 6, 2<br>9, 6, 6, 3 |
| AKL3B | A | 0·136 | 9, 6, 6, 1<br>9, 6, 6, 1<br>9, 6, 6, 1 |
| AKL3C | A | 0·144 | 9, 6, 6, 1<br>9, 6, 6, 1<br>9, 6, 6, 1 |
| AKL3D | A | 0·166 | 9, 6, 6, 6, 3<br>9, 6, 6, 6, 1<br>9, 6, 6, 4 |
| AKL3E | A | 0·185 | 9, 6, 6, 4<br>9, 6, 6, 6, 6, 1<br>9, 6, 6, 4 |
| AKL3F | A | 0·215 | 12, 6, 6, 6, 6, 6<br>12, 6, 6, 6, 6, 6<br>12, 6, 6, 6, 6, 3 |
| AKN3A | B | 0·104 | 9, 6, 6, 6, 5<br>9, 6, 6, 6, 6, 1<br>9, 6, 6, 1 |
| AKN3B | B | 0·136 | 9, 6, 6, 6, 6, 1<br>9, 6, 6, 1<br>9, 6, 6, 4 |
| AKN3C | B | 0·144 | 9, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 1 |
| AKN3D | B | 0·166 | 9, 6, 6, 4<br>9, 6, 6, 6, 6, 1<br>9, 6, 6, 4 |
| AKN3E | B | 0·185 | 9, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 1<br>9, 6, 6, 2 |
| AKN2F | B | 0·215 | 12, 6, 6, 6, 6, 1<br>12, 6, 6, 6, 6, 1<br>12, 6, 6, 6, 1 |
| AKO3A | C | 0·104 | 9, 6, 6, 2<br>9, 6, 6, 1<br>9, 6, 6, 3 |
| AKO3B | C | 0·136 | 9, 6, 6, 1<br>9, 6, 6, 6, 1<br>9, 6, 6, 1 |
| AKO3C | C | 0·144 | 9, 6, 6, 3<br>9, 6, 6, 1<br>9, 6, 6, 2 |
| AKO3D | C | 0·166 | 9, 6, 6, 6, 6, 2<br>9, 6, 6, 1<br>9, 6, 6, 1 |
| AKO3E | C | 0·185 | 9, 6, 6, 1<br>9, 6, 6, 1<br>9, 6, 6, 1 |
| AKO3F | C | 0·215 | 12, 6, 6, 3<br>12, 6, 6, 4<br>12, 6, 6, 3 |

from the same end of the coil as the tensile test pieces. The distance between the jaws was set at 6 in. for all the samples, but additional tests on 3-in. lengths were made on the small diameter wires.

The results of these tests are given in Table 5.

### WRAP TESTS.

The British Engineering Standards Association Specification for hard drawn copper wire states that "the test sample shall be closely lapped six times round wire of its own diameter, unlapped, and again closely lapped round wire of its own diameter in the same direction as the first lapping without breaking."

Tests were made on these lines, but the wrapping and unwrapping was continued until fracture occurred. It was found necessary to wrap on 9 or 12 turns in the first wrapping, and then wrap and unwrap 6 turns as required in the test, so as to make the unwrapping operation easier during the last few turns.

The results of these tests are given in Table 6. In this table the results are stated in the following form—the 1st, 3rd, 5th, etc., numbers represent the wrapping operation, the intermediate numbers the unwrapping operation.

### COMPARISON OF PERCENTAGE EXTENSION WITH TWIST AND WRAP TESTS.

An examination of Table 7 shows that the wire of maker B, although giving higher values from the twist test than that obtained from other makers, shows no superiority as regards extension.

The results from the wrap tests, taken as a whole, tend to agree with the twist tests in this respect.

### SUMMARY OF RESULTS.

The results given in the previous tables have been summarized in Table 7 below, average values being given in place of the full detail results, and the relative conductivity at 20° C. has also been included.

TABLE 7.

*Summary of Results of Tests on Single Wires supplied separately* (see Table 1A).

| Nominal Diameter of Wire, inch | Primitive Limit of Proportionality, tons per sq. in. | Ultimate Stress | | Extension, inch | | | | Modulus of Elasticity, lb. per sq. in. $\times 10^{-6}$ | | Average Twists on | | Minimum Value for Wrap Test | Relative Conductivity at 20°C. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Slow Loading, tons per sq. in. | Quick Loading, tons per sq. in. | Slow Loading on | | Quick Loading on | | | | | | | |
| | | | | 10 in. | 2 in. | 10 in. | 2 in. | 1st | 2nd | 6 in. | 3 in. | | |
| N.P.L. Mark, AKL<br>Maker, A | | | | | | | | | | | | | |
| 0·104 | 10·9 | 28·4 | 30·3 | 0·10 | 0·06 | 0·12 | 0·07 | 18·0 | 18·7 | 40 | 30 | 9, 6, 6 | 98·4 |
| 0·136 | 6·4 | 27·5 | 28·7 | 0·12 | 0·07 | 0·16 | 0·08 | 18·3 | 18·9 | 30 | 15 | 9, 6, 6 | 98·4 |
| 0·144 | 6·2 | 27·6 | 28·4 | 0·14 | 0·09 | 0·18 | 0·11 | 18·7 | 19·6 | 32 | — | 9, 6, 6 | 98·8 |
| 0·166 | 5·3 | 26·0 | 26·9 | 0·13 | 0·09 | 0·21 | 0·12 | 18·3 | 18·5 | 31 | — | 9, 6, 6 | 99·1 |
| 0·185 | 7·1 | 25·5 | 26·2 | 0·19 | 0·13 | 0·24 | 0·13 | 18·2 | 18·3 | 23 | — | 9, 6, 6 | 99·2 |
| 0·215 | 4·0 | 22·7 | 23·4 | 0·19 | 0·14 | 0·29 | 0·16 | 16·7 | 17·0 | 25 | — | 12, 6, 6, 6, 6 | 99·2 |
| N.P.L. Mark, AKN<br>Maker, B | | | | | | | | | | | | | |
| 0·104 | 11·5 | 28·3 | 29·0 | 0·10 | 0·06 | 0·14 | 0·06 | 17·5 | 18·4 | 80 | 44 | 9, 6, 6 | 98·5 |
| 0·136 | 7·5 | 27·8 | 28·4 | 0·10 | 0·07 | 0·13 | 0·07 | 17·8 | 18·2 | 59 | 32 | 9, 6, 6, 6 | 98·5 |
| 0·144 | 6·8 | 27·2 | 27·9 | 0·11 | 0·07 | 0·14 | 0·08 | 17·5 | 18·1 | 52 | — | 9, 6, 6, 6, 6 | 97·9 |
| 0·166 | 6·9 | 26·8 | 27·4 | 0·13 | 0·09 | 0·17 | 0·09 | 18·2 | 18·8 | 49 | — | 9, 6, 6 | 98·8 |
| 0·185 | 9·6 | 26·6 | 27·3 | 0·17 | 0·09 | 0·18 | 0·10 | 16·9 | 17·0 | 36 | — | 9, 6, 6 | 98·8 |
| 0·215 | 8·2 | 26·8 | 27·0 | 0·20 | 0·11 | 0·20 | 0·10 | 16·4 | 17·2 | 37 | — | 12, 6, 6, 6 | 98·2 |
| N.P.L. Mark, AKO<br>Maker, C | | | | | | | | | | | | | |
| 0·104 | 9·4 | 28·2 | 29·7 | 0·15 | 0·08 | 0·21 | 0·09 | 18·4 | 19·3 | 65 | 39 | 9, 6, 6 | 97·7 |
| 0·136 | 9·4 | 28·1 | 28·5 | 0·12 | 0·07 | 0·20 | 0·10 | 18·4 | 19·0 | 47 | 26 | 9, 6, 6 | 97·9 |
| 0·144 | 7·6 | 28·3 | 29·0 | 0·10 | 0·07 | 0·19 | 0·10 | 18·2 | 18·7 | 51 | — | 9, 6, 6 | 97·9 |
| 0·166 | 6·1 | 27·1 | 27·9 | 0·16 | 0·08 | 0·26 | 0·12 | 18·3 | 18·8 | 38 | — | 9, 6, 6 | 97·9 |
| 0·185 | 9·6 | 27·9 | 28·1 | 0·19 | 0·11 | 0·21 | 0·11 | 17·8 | 18·2 | 33 | — | 9, 6, 6 | 97·5 |
| 0·215 | 6·1 | 26·9 | 27·4 | 0·12 | 0·10 | 0·26 | 0·12 | 17·8 | 18·4 | 23 | — | 12, 6, 6 | 97·7 |

## II. MECHANICAL TESTS ON SHORT STRANDED CABLES.

Details of the stranded cables on which the tests were carried out are given in Table 8.

TABLE 8.

*Stranded Cables.*

| N.P.L. Mark | Maker | Type | Diameter of Cable, inch |
|---|---|---|---|
| AKL4A | A | 3/·166 | 0·34 |
| AKL4B | A | 7/·166 | 0·50 |
| AKL4C | A | 7/·215 | 0·66 |
| AKL4D | A | 19/·144 | 0·72 |
| AKL4E | A | 19/·166 | 0·81 |
| AKL4F | A | 37/·144 | 1·00 |
| AKN4A | B | 3/·166 | 0·34 |
| AKN4B | B | 7/·166 | 0·50 |
| AKN4C | B | 7/·215 | 0·66 |
| AKN4D | B | 19/·144 | 0·72 |
| AKN4E | B | 19/·166 | 0·81 |
| AKN4F | B | 37/·144 | 1·00 |
| AKO4A | C | 3/·166 | 0·34 |

### DETERMINATION OF BREAKING LOAD.

*Apparatus Employed.*—The tensile tests on the complete cables were carried out on a 50-ton single lever testing machine. A set of special friction grips were made in which three split circular wedges embraced the cable under test. This form of grip is known to have been successful with another type of vertical machine, but owing to the small clearances in the machine used, it was found impossible to drive the wedges home with the cable in place and it became necessary to discard them.

A new type of grip was designed and made in the Engineering Department Workshop, N.P.L. Two split taper guides engaged with the spherical seat of the top of the testing machine. The grips are 14 in. long and shaped out to a square. The grips were successively machined out to suit the range of sizes of cables under test. It was found convenient to divide the 13 cables under test into five series. For each series, the square of the wedge grips was machined out accordingly. The surface of the grips was very slightly roughened by means of light chisel marks. Using these grips, no trouble whatever has been encountered due to slipping of the cable under test. It was not found necessary to protect the cable under test by means of any wrapping wire. The length of the grips so reduced the bearing pressure on the cable that the surface of the wires in contact with the grips was only roughened. Out of 27 cables tested to destruction only one broke in the grips.

*Strength of constituent wires of the cables.*—To determine the efficiencies of the various cables, it was originally intended to compare the cable breaking stress with the results of single wire tests. A few preliminary tests showed that great differences existed between the actual and stated strengths of the wire used in the cables. It was also found that up to as much as 25 per cent difference in strength existed between wires of the same cable. It was decided, therefore, to determine the breaking load of the wires by testing to destruction each wire of which the cable was composed. Thus, 187 wire tests have been carried out, in addition to the 27 samples of cable tested to destruction. The wire tests were carried out on the 2-ton single-lever machine.

*Selection of samples.*—A length of 9 ft. was cut off from each cable. One length of 4 ft. was cut off each end of this length, one such length being used for the determination of the breaking load and the other for the determination of the limit of proportionality, modulus, etc. The central portion was unstranded, and each wire tested to destruction.

*Extension at fracture.*—Gauge marks, 8 in. apart, were made on the cable at the commencement of the tests. In many cases the cable unstranded in the vicinity of the fracture and it was found impossible to measure the elongation. In the majority of cases, corresponding ends of broken wires were misplaced and it was extremely difficult to place the fractured ends in their true relative positions. The measured elongations are, therefore, given chiefly for their relative values. The accuracy of their values cannot be relied upon.

*Conditions of tests.*—The length of cable between the grips was 14 in. The tests on the copper cables were carried out as nearly as possible in conformity with the British Engineering Standards Association Specification for hard drawn copper wire, viz. 9/10 of the breaking load was applied in 5 seconds and the remaining 1/10 in 5 seconds. The latter condition was not always fulfilled, as, usually, after the apparent maximum load had been applied and the beam of the testing machine began to fall, the cable seemed to recover, and further load had to be applied. The results of tests to fracture on the cables and constituent wires are given in Table 9.

Table 10 gives the collected results of the breaking stresses of the short lengths of cables and compares them with the total strength of their constituent wires and also the results of the single wire tests.

Column 1 gives particulars of the cables and their ultimate stresses.

Column 2 gives the ultimate stress of the constituent wires.

Column 3 is a summary of the single-wire tests. The values obtained for slow and quick loading are inserted.

Column 4 gives the percentage strength of the cable as compared with that of the constituent wires, so that

Efficiency on constituent wires, per cent

$$= \frac{\text{Ultimate strength of cable (tons per sq. in.)}}{\text{Total ultimate strength of constituent wires (tons per sq. in.)}} \times 100$$

### TABLE 9.

*Tensile Strength of Short Cables and of Constituent Wires.*

| N.P.L. Mark | Maker | Type | Short Cables | | | | Constituent Wires | |
|---|---|---|---|---|---|---|---|---|
| | | | Cross-sectional Area, sq. in. | Breaking Load, tons | Ultimate Stress, tons/in.$^2$ | Per cent Extension on 8 in. | Total Breaking Load, tons | Ultimate Stress, tons/in.$^2$ |
| AKL4A | A | 3/·166 | 0·0647 | 1·58 | 24·4 | 5 | 1·65 | 25·5 |
| AKL4B | A | 7/·166 | 0·1512 | 3·79 | 25·1 | 5 | 3·92 | 25·9 |
| AKL4C | A | 7/·215 | 0·2525 | 5·74 | 22·7 | 4 | 5·95 | 23·6 |
| AKL4D | A | 19/·144 | 0·3063 | 7·78 | 25·4 | 2 | 8·36 | 27·3 |
| AKL4E | A | 19/·166 | 0·4057 | 10·3 | 25·4 | — | 10·6 | 26·1 |
| AKL4F | A | 37/·144 | 0·5920 | 15·0 | 25·3 | 3 | 16·1 | 27·2 |
| AKN4A | B | 3/·166 | 0·0656 | 1·61 | 24·6 | 6 | 1·68 | 25·6 |
| AKN4B | B | 7/·166 | 0·1506 | 3·93 | 26·1 | 5 | 4·12 | 27·4 |
| AKN4C | B | 7/·215 | 0·2297 | 5·92 | 25·8 | 4 | 6·29 | 27·4 |
| AKN4D | B | 19/·144 | 0·3068 | 7·92 | 25·8 | 5 | 8·49 | 27·7 |
| AKN4E | B | 19/·166 | 0·4049 | 9·97 | 24·6 | — | 10·95 | 27·0 |
| AKN4F | B | 37/·144 | 0·5983 | 15·34 | 25·6 | 2 | 16·10 | 26·9 |
| AKO4A | C | 3/·166 | 0·0648 | 1·70 | 26·2 | 6 | 1·76 | 27·2 |

### TABLE 10.

*Tensile Strength of Short Cables and their Constituent Wires and of Single Wires supplied separately.*

| Column 1 | | | | Column 2 | Column 3 | | | | Column 4 | Column 5 | Column 6 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tests on Short Cables | | | | Tests on Constituent Wires, Ultimate Stress of Wires Forming Cable, tons/in.$^2$ | Tests on Single Wires supplied separately | | | | Efficiency on Constituent Wires, per cent | Efficiency on Single Wire, Slow Loading, per cent | Efficiency on Single Wire, Quick Loading, per cent |
| N.P.L. Mark | Maker | Type | Ultimate Stress of Cable, tons/in.$^2$ | | Maker | Diameter, in. | Ultimate Stress, tons/in.$^2$ | | | | |
| | | | | | | | Slow Loading | Quick Loading | | | |
| AKL4A | A | 3/·166 | 24·4 | 25·5 | A | 0·166 | 26·0 | 26·9 | 96 | 94 | 91 |
| AKL4B | A | 7/·166 | 25·1 | 25·9 | A | 0·166 | 26·0 | 26·9 | 97 | 97 | 93 |
| AKL4C | A | 7/·215 | 22·7 | 23·6 | A | 0·215 | 22·7 | 23·4 | 96 | 100 | 97 |
| AKL4D | A | 19/·144 | 25·4 | 27·3 | A | 0·144 | 27·6 | 28·4 | 93 | 92 | 89 |
| AKL4E | A | 19/·166 | 25·4 | 26·1 | A | 0·166 | 26·0 | 26·9 | 97 | 98 | 94 |
| AKL4F | A | 37/·144 | 25·3 | 27·2 | A | 0·144 | 27·6 | 28·4 | 93 | 92 | 89 |
| AKN4A | B | 3/·166 | 24·6 | 25·6 | B | 0·166 | 26·8 | 27·4 | 96 | 92 | 90 |
| AKN4B | B | 7/·166 | 26·1 | 27·4 | B | 0·166 | 26·8 | 27·4 | 95 | 97 | 95 |
| AKN4C | B | 7/·215 | 25·8 | 27·4 | B | 0·215 | 26·8 | 27·0 | 94 | 96 | 96 |
| AKN4D | B | 19/·144 | 25·8 | 27·7 | B | 0·144 | 27·2 | 27·9 | 93 | 95 | 93 |
| AKN4E | B | 19/·166 | 24·6 | 27·0 | B | 0·166 | 26·8 | 27·4 | 91 | 92 | 90 |
| AKN4F | B | 37/·144 | 25·6 | 26·9 | B | 0·144 | 27·2 | 27·9 | 95 | 94 | 92 |
| AKO4A | C | 3/·166 | 26·2 | 27·2 | C | 0·166 | 27·1 | 27·9 | 96 | 97 | 94 |

Columns 5 and 6 give the percentage strength of the cable as compared with the results obtained on the single wire tests.

Efficiency on single wire, per cent

$$= \frac{\text{Ultimate strength of cable (tons per sq. in.)}}{\text{Ultimate strength of single wire (tons per sq. in.)}} \times 100$$

## Determination of the Limit of Proportionality and Modulus.

The same grips were used as previously described. The length of cable under test between the edges of the grips was 14 in. A Ewing extensometer was used to measure the strains which were observed on a length of 8 in. The primitive limit of proportionality and the modulus, at first loading, were obtained by loading up in equal steps to a point just beyond the load where the limit of proportionality was observed. The load was then removed and a second modulus obtained by loading up again to the same point.

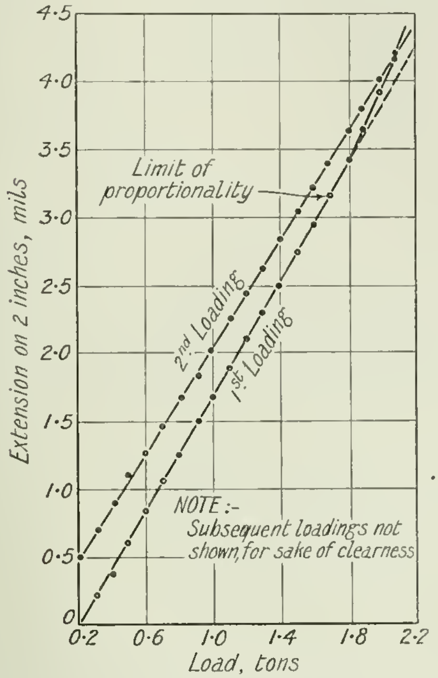


Fig. 4.—Typical Load-Extension Curves of Small Short Stranded Cables (7/·166).

It will be noted that the strains thus obtained were those due to the outside wires only while the corresponding stresses were calculated for the total area of the cable under test. After a number of cables had been tested, a comparison of the results obtained with those of the single wire tests showed great differences. In nearly every case the limit of proportionality and the value of Young's Modulus obtained for the cable were much higher and lower respectively than those obtained for the single wires. At the same time the regularity of the plotted points shows that the results obtained are the true strains for the outside wires and indicates that the stress distribution across the cable is not uniform. It was thought that if the loading were repeated a sufficient number of times, the value obtained for the modulus would, perhaps, tend to approach the true value for the material of which the cable was composed. Accordingly for the remainder of the cables the modulus was determined for the first, second, third, fourth, fifth and tenth loadings. The results show that the modulus under successive loadings tends to approach a limiting maximum value, but in the majority of cables tested this limiting value was much below the true value of the material of which the cable was composed.

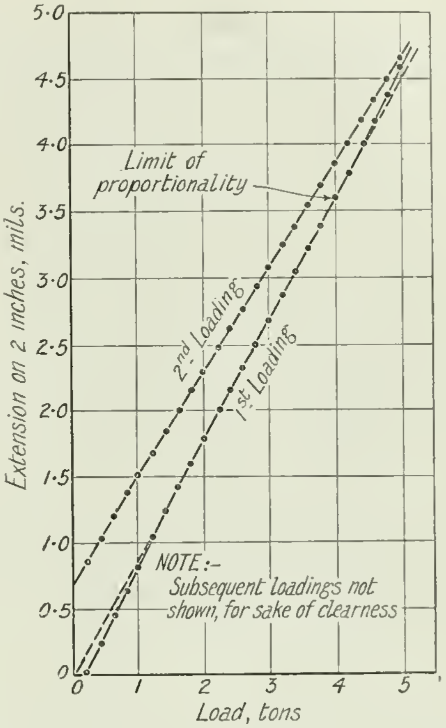


Fig. 5.—Typical Load-Extension Curves of Large Short Stranded Cables (19/·166).

The results of the tests on long lengths of cable reveal some interesting facts on this point and seem to indicate that the value of the limit of proportionality and modulus obtained by tensile tests on short lengths of cables are unreliable and inaccurate.

*Results.*—Table 11 gives the values obtained on short lengths of cable for the limit of proportionality and Young's Modulus under successive loadings. The results of similar tests on the single wires supplied separately are included for purposes of comparison.

Representative load-extension curves obtained are shown in Figs. 4 and 5.

## III. MECHANICAL TESTS ON LONG STRANDED CABLES.

Details of the stranded cables on which the tests were carried out are given in Table 8 in Section II. The cables numbered a total of 13. The tests required were the determination of Young's Modulus ($E$) under tensile loading employing a test length of 100 yards.

### Method of Test.

The cable under test was maintained in a horizontal plane and was floated in mid-air by means of suspenders attached to suspension cables tightly stretched. Loading was applied at both ends by means of screwed bars. Two measuring microscopes, spaced 100 yards apart, were used to observe the resulting strains.

Table 11.

*Limit of Proportionality and Young's Modulus for Short Cables and for Single Wires supplied separately.*

| Tests on Short Cables | | | | | | | | | | | | Tests on Single Wires supplied separately | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N.P.L. Mark | Maker | Type | Cross Sectional Area, sq. in. | Primitive Limit of Proportionality | | Modulus ($E$), lb./in.² × $10^{-6}$ | | | | | | Maker | Diameter, in. | Stress at Limit of Proportionality, tons/in.² | Modulus ($E$) lb./in.² × $10^{-6}$ | |
| | | | | Load, tons | Stress, tons/in.² | 1st | 2nd | 3rd | 4th | 5th | 10th | | | | 1st | 2nd |
| AKL4A | A | 3/·166 | 0·0647 | 0·66 | 10·2 | 13·2 | 16·6 | — | — | — | — | A | 0·166 | 5·3 | 18·3 | 18·5 |
| AKL4B | A | 7/·166 | 0·1512 | 1·70 | 11·2 | 13·4 | 16·2 | 16·7 | 16·5 | 16·7 | 16·5 | A | 0·166 | 5·3 | 18·3 | 18·5 |
| AKL4C | A | 7/·215 | 0·2525 | 2·50 | 9·9 | 11·9 | 15·5 | 14·2 | 14·3 | 14·3 | 14·4 | A | 0·215 | 4·0 | 16·7 | 17·0 |
| AKL4D | A | 19/·144 | 0·3063 | 3·60 | 11·8 | 11·6 | 14·9 | 14·8 | 14·8 | 14·8 | 14·8 | A | 0·144 | 6·2 | 18·7 | 19·6 |
| AKL4E | A | 19/·166 | 0·4057 | 5·80 | 14·3 | 10·2 | 14·7 | 15·5 | 16·0 | 16·0 | 16·2 | A | 0·166 | 5·3 | 18·3 | 18·5 |
| AKL4F | A | 37/·144 | 0·5920 | 5·40 | 9·1 | 7·3 | 11·6 | 12·1 | 13·5 | 13·5 | 13·8 | A | 0·144 | 6·2 | 18·7 | 19·6 |
| AKN4A | B | 3/·166 | 0·0656 | 0·65 | 9·9 | 11·8 | 13·7 | — | — | — | — | B | 0·166 | 6·9 | 18·2 | 18·8 |
| AKN4B | B | 7/·166 | 0·1506 | 1·60 | 10·6 | 13·8 | 15·3 | 15·6 | 15·6 | 15·6 | 15·6 | B | 0·166 | 6·9 | 18·2 | 18·8 |
| AKN4C | B | 7/·215 | 0·2297 | 2·20 | 9·6 | 12·1 | 13·1 | 12·8 | 12·8 | 12·9 | 12·9 | B | 0·215 | 8·2 | 16·4 | 17·2 |
| AKN4D | B | 19/·144 | 0·3068 | 3·20 | 10·4 | 12·5 | 15·3 | 14·7 | 14·7 | 14·8 | 14·8 | B | 0·144 | 6·8 | 17·5 | 18·1 |
| AKN4E | B | 19/·166 | 0·4049 | 4·00 | 9·9 | 12·2 | 14·2 | 14·1 | 14·6 | 14·6 | 14·7 | B | 0·166 | 6·9 | 18·2 | 18·8 |
| AKN4F | B | 37/·144 | 0·5983 | 5·80 | 9·7 | 10·6 | 13·8 | 13·9 | 13·9 | 14·1 | 13·9 | B | 0·144 | 6·8 | 17·5 | 18·1 |
| AKO4A | C | 3/·166 | 0·0648 | 0·80 | 12·4 | 14·2 | 16·9 | — | — | — | — | C | 0·166 | 6·1 | 18.3 | 18·8 |

### Description of Apparatus.

A preliminary line of levels along the site chosen revealed a rise in the ground of about 6·5 in. on the 100-yard length. It was decided to keep the cable under test and the suspensory supporting posts truly horizontal. The posts carrying the suspension wires were spaced at 10-ft. intervals. They were fitted with substantial footings and a cross-piece to prevent end movement. A 2-in. slot was provided through which the cable under test passed. Great attention was given to correct alignment, and when the posts were finally erected, a line of levels showed that no post was more than 0·3 in. out of the mean horizontal line containing the top of the posts. It was considered that this error was too great to allow this line of posts to be used as a reference line for the cable under test and the final reference line was obtained as follows: A stout nail was driven into the side of each post, the position of each nail being calculated from the known error on the top of each post. A final line of levels was taken on the nails and in no case was an error found of more than 1/100 part of a foot from the true horizontal. A long length of No. 8 S.W.G. steel wire (60 tons per sq. in.) was stretched from end to end of the apparatus and strained to a stress (estimated) of about 40 tons per sq. in. This wire rested on the tops of the nails and served as a horizontal datum line. Two steel cables (7/16–60 tons per sq. in.) were used as suspension wires. These rested on the tops of the supporting posts and were secured at the ends to standard P.O. stay rods (6 ft. 0 in. × ⅝ in.) and were strained evenly at intervals of 2 ft. A hoop-iron clip maintained these cables at a distance of 2 in. apart and served as bridges for adjustable wire suspenders supporting the cable under test. The tops of these suspenders were screwed and gave the adjustment necessary to bring the cable under test into a horizontal plane. This was effected by placing a spirit level resting on top of the cable under test and the datum wire previously referred to. No trouble was experienced in levelling up, half an hour being the usual time necessary to level the cable at the 150 points of suspension. The regularity of the stress-strain curves obtained during the tests indicates that this method of levelling, although simple, was satisfactory and accurate.

The load was recorded at one end by means of the dynamometer belonging to the N.P.L. Engineering Department. It consisted essentially of an accurately fitting piston of 2 in. diameter sliding in a cylinder. The load on the cable (and piston) was transmitted as a pressure through the contained fluid (castor oil) to a pressure gauge. The total load on the cable was thus equal to the pressure gauge reading multiplied by $\pi$ (3·142). A preliminary dead-weight calibration of the dynamometer showed that it was correct to about 5 lb. per sq. in. Two pressure gauges were used, of 1·5 tons per sq. in. and 1 600 lb. per sq. in. capacity respectively, and were calibrated at frequent intervals between the tests.

The actual straining was done by means of two straining blocks, one at each end, fitted with a fine thread. To reduce friction, each nut was fitted with a pair of spherical washers.

Two centre punch marks were made on the cable under test at a distance of 100 yards apart. The movement of each of these marks was observed by means of a measuring microscope reading to 1/100 mm.

TABLE 12.

*Limit of Proportionality and Young's Modulus for 100-yard Lengths of Cables.*

| N.P.L. Mark | AKL4A | AKL4B | AKL4C | AKL4D | AKL4E | AKL4F | AKN4A | AKN4B | AKN4C | AKN4D | AKN4E | AKN4F | AKO4A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maker | A | A | A | A | A | A | B | B | B | B | B | B | C |
| Type | 3/·166 | 7/·166 | 7/·215 | 19/·144 | 19/·166 | 37/·144 | 3/·166 | 7/·166 | 7/·215 | 19/·144 | 19/·166 | 37/·144 | 3/·166 |
| Area, square inch | 0·0647 | 0·1512 | 0·2525 | 0·3063 | 0·4057 | 0·5920 | 0·0656 | 0·1506 | 0·2297 | 0·3068 | 0·4049 | 0·5983 | 0·0648 |
| Load at limit of proportionality, tons | 0·41 | 0·63 | 1·42 | — | — | — | 0·71 | 1·02 | 2·67 | 2·79 | 2·83 | — | 0·47 |
| Stress at limit of proportionality, tons per in.² | 6·3 | 4·2 | 5·6 | — | — | — | 10·8 | 6·8 | 11·6 | 9·1 | 7·0 | — | 7·3 |
| Modulus ($E$), lb. per in.² × 10⁻⁶:— | | | | | | | | | | | | | |
| 1st loading | 16·8 | 17·1 | 12·3 | 9·5 | 17·1 | 15·1 | 12·2 | 15·0 | 12·4 | 13·0 | 16·0 | 15·5 | 14·8 |
| 2nd " | 18·2 | 18·4 | 16·0 | 15·2 | 18·2 | 15·3 | 15·7 | 16·7 | 17·0 | 16·1 | 16·4 | 15·3 | 18·1 |
| 3rd " | 18·2 | 18·4 | 18·5 | 16·4 | 18·4 | 17·4 | 16·4 | 17·3 | 17·4 | 17·6 | 16·7 | 15·4 | 18·0 |
| 4th " | 18·4 | 18·4 | 18·4 | 17·3 | 18·9 | 16·6 | 17·8 | 17·3 | 18·2 | 17·7 | 16·3 | 15·3 | 18·6 |
| 5th " | 18·4 | 18·4 | 15·5 | 18·7 | 18·8 | 16·7 | 18·0 | 17·8 | 18·2 | 17·7 | 16·7 | 15·7 | 18·9 |
| 6th " | — | — | — | — | — | 16·9 | — | — | — | — | — | — | — |
| Temperature during test, ° C. | 13 | 8 | 13 | 5 | 4 | 4 | 12 | 5 | 11 | 6 | 4 | 12 | 8 |
| | *Tests on single wires supplied separately, for comparison.* | | | | | | | | | | | | |
| Maker | A | A | A | A | A | A | B | B | B | B | B | B | C |
| Diameter, inch | 0·166 | 0·166 | 0·215 | 0·144 | 0·166 | 0·144 | 0·166 | 0·166 | 0·215 | 0·144 | 0·166 | 0·144 | 0·166 |
| Stress at limit of proportionality, tons per in.² | 5·3 | 5·3 | 4·0 | 6·2 | 5·3 | 6·2 | 6·9 | 6·9 | 8·2 | 6·8 | 6·9 | 6·8 | 6·1 |
| Modulus ($E$), lb. per in.² × 10⁻⁶:— | | | | | | | | | | | | | |
| 1st loading | 18·3 | 18·3 | 16·7 | 18·7 | 18·3 | 18·7 | 18·2 | 18·2 | 16·4 | 17·5 | 18·2 | 17·5 | 18·3 |
| 2nd " | 18·5 | 18·5 | 17·0 | 19·6 | 18·5 | 19·6 | 18·8 | 18·8 | 17·2 | 18·1 | 18·8 | 18·1 | 18·8 |

* This cable (AKN4F) unfortunately became kinked in one place while uncoiling from the drum. The kink was apparent throughout the test, and partly accounts for the low values obtained for the Modulus ($E$).

TABLE 13.

*Alteration of Modulus of 100-yard Lengths of Cables by Repeated Loadings.*

| N.P.L. Mark | Maker | Type of Cable | Modulus of Elasticity, lb. per sq. in. | | Ratio $\frac{A}{B}$ per cent | Percentage of Breaking Load applied |
|---|---|---|---|---|---|---|
| | | | A<br>1st Loading | B<br>5th Loading | | |
| AKL4A | A | 3/·166 | 16·8 × 10⁶ | 18·4 × 10⁶ | 91 | 50 |
| AKL4B | A | 7/·166 | 17·1 | 18·4 | 93 | 33 |
| AKL4C | A | 7/·215 | 12·3 | 18·5 | 66 | 52 |
| AKL4D | A | 19/·144 | 9·5 | 18·7 | 51 | 38 |
| AKL4E | A | 19/·166 | 17·1 | 18·8 | 91 | 31 |
| AKL4F | A | 37/·144 | 15·1 | 16·7 | 90 | 25 |
| AKN4A | B | 3/·166 | 12·2 × 10⁶ | 18·0 × 10⁶ | 68 | 58 |
| AKN4B | B | 7/·166 | 15·0 | 17·8 | 84 | 36 |
| AKN4C | B | 7/·215 | 12·4 | 18·2 | 68 | 53 |
| AKN4D | B | 19/·144 | 13·0 | 17·7 | 73 | 40 |
| AKN4E | B | 19/·166 | 16·0 | 16·7 | 96 | 32 |
| AKN4F | B | 37/·144 | 15·5 | 15·7 | 99 | 25 |
| AKO4A | C | 3/·166 | 14·8 | 18·9 | 78 | 42 |

### SITE OF APPARATUS.

The apparatus was erected alongside a wall in the N.P.L. sports field and was completely shaded by trees. Each test was carried out on a dull, windless day, and it is believed that the errors due to varying temperature were inappreciable. A preliminary experiment was made to determine the variation of temperature along the apparatus. Fourteen thermometers were distributed along the test length and gave the following readings (degrees centigrade) :—

3·8, 3·7, 3·8, 3·7, 3·8, 4·0,* 3·65, 3·8, 3·9, 3·8, 3·7, 3·8, 3·7, 3·7.

In view of the regularity of these readings it was considered only necessary to record temperatures at each end of the apparatus during test. The temperature readings were taken frequently during the test, and during no test was a greater variation than 1° C. recorded. The modulus given in the results may, therefore, be taken as the true modulus for the temperature stated.

### EFFECT OF TEMPERATURE COEFFICIENT ON YOUNG'S MODULUS.

The usual formula for temperature coefficient on Young's Modulus is as follows :—

$$E = E_{15} \left\{ 1 - a \ (t - 15) \right\}$$

where $E$ = value for Young's Modulus at temperature $t$° C.

$E_{15}$ = value for Young's Modulus at temperature 15° C.

$a$ = constant.

The following values for $a$ are taken from "Physical and Chemical Constants," by Kaye and Laby :—

| Material | Value of $a$ |
|---|---|
| Aluminium .. .. .. | $21 \cdot 3 \times 10^{-4}$ |
| Copper .. .. .. | $3 \cdot 64 \times 10^{-4}$ |
| Steel .. .. .. | $2 \cdot 4 \times 10^{-4}$ |

Inserting these values for $t = 5$° C. we obtain :—

(1) For aluminium .. .. $E_5 = E_{15} \times 1 \cdot 0213$

(2) For copper .. .. .. $E_5 = E_{15} \times 1 \cdot 0036$

(3) For steel .. .. .. $E_5 = E_{15} \times 1 \cdot 0024$

The minimum temperature recorded during an actual test was 4° C. It will be seen that the temperature correction for aluminium cables is just within the accuracy of the experiment, whilst it can be neglected in the case of copper and steel cables.

### RESULTS OF TESTS.

The results of the tests are given in Table 12. For purposes of comparison, the limit of proportionality and modulus obtained from the tests on single wires are included.

A typical load-extension curve is shown in Fig. 6. In nine of the thirteen tests recorded the limit of proportionality was strongly marked. For two of the cables, N.P.L. Nos. AKL4D and AKL4E, the limit of proportionality was masked by other strains. For cables Nos. AKL4F and AKN4F the maximum safe load for the dynamometer (3·8 tons) was insufficient to disclose the limit of proportionality. It will be noted that the results show that cables consisting of, and up to, 19 wires give a value for the Modulus ($E$) approximately equal to that obtained for a single wire. Two of the 19-wire cables and the two 37-wire cables give lower values of $E$. To ascertain whether the low value for a large cable was due to small non-elastic strains which would disappear with application of load for considerable time, a special test was carried out on a cable (37 wires), N.P.L. No. AKL4F. The cable, on removal from the drum, was loaded to 3·8 tons. This load, which was probably slightly lower than the "primitive" limit of proportionality, was applied to the cable for two days. The load was then removed and applied five times, load-elongation diagrams being obtained in each case. The cable was removed from the machine and allowed to rest for a fortnight under no load. The cable was replaced in the machine and the load of 3·8 tons applied continuously for one week. At the end of the week, a load-elongation diagram was again obtained. The values obtained for the Modulus ($E$) are as follows (see also Table 12) :—

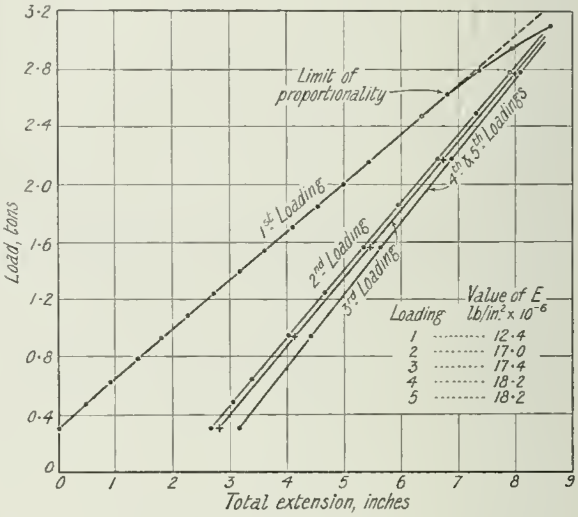


FIG. 6.—Typical Load-Extension Curves of 100-yard Lengths of Cables (7/·215).

| | |
|---|---|
| N.P.L. Mark .. .. .. .. | AKL4F |
| Maker .. .. .. .. | A |
| Type .. .. .. .. .. | 37/·144 |
| Value of Modulus ($E$), lb. per in.² $\times 10^{-6}$ :— | |
| 1st loading .. .. .. | 15·1 |
| 2nd ,, .. .. .. | 15·3 |
| 3rd ,, .. .. .. | 17·4 |
| 4th ,, .. .. .. | 16·6 |
| 5th ,, .. .. .. | 16·7 |
| 6th ,, .. .. .. | 16·9 |
| (After application of maximum load for one week). | |

To ascertain the amount of increase of the modulus of elasticity due to repeated loadings, the loading of

---

* This thermometer was placed at a portion of the cable where it passed a small hut used for storing hay.

### Table 14.

*Pitch and Lay of Constituent Wires of 100-yard Lengths of Cables.*

| Column 1 | | | Column 2 | | | Column 3 | | | Column 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Measured Pitch Diameter, in. | | | Measured Pitch of Wires, in. | | | Lay of Wires | | |
| N.P.L. Mark | Maker | Type of Cable | *a* | *b* | *c* | *A* | *B* | *C* | $\frac{A}{a}$ | $\frac{B}{b}$ | $\frac{C}{c}$ |
| AKL4A | A | 3/·166 | 0·169 | — | — | 4·25 R | — | — | 25 R | — | — |
| AKL4B | A | 7/·166 | 0·334 | — | — | 6·5 R | — | — | 19½ R | — | — |
| AKL4C | A | 7/·215 | 0·445 | — | — | 9·5 R | — | — | 21 R | — | — |
| AKL4D | A | 19/·144 | 0·586 | 0·296 | — | 8·0 R | 9·0 L | — | 13½ R | 30½ L | — |
| AKL4E | A | 19/·166 | 0·664 | 0·329 | — | 10·5 R | 10·0 L | — | 16 R | 30½ L | — |
| AKL4F | A | 37/·144 | 0·861 | 0·581 | 0·291 | 13·0 R | 8·5 L | 8·0 R | 15 R | 14½ L | 27½ R |
| AKN4A | B | 3/·166 | 0·169 | — | — | 3 R | — | — | 18 R | — | — |
| AKN4B | B | 7/·166 | 0·334 | — | — | 5 R | — | — | 15 R | — | — |
| AKN4C | B | 7/·215 | 0·450 | — | — | 5 R | — | — | 11 R | — | — |
| AKN4D | B | 19/·144 | 0·581 | 0·291 | — | 7½ L | 6½ R | — | 13 L | 22½ R | — |
| AKN4E | B | 19/·166 | 0·669 | 0·329 | — | 6½ R | 5½ L | — | 9½ R | 16½ L | — |
| AKN4F | B | 37/·144 | 0·871 | 0·581 | 0·291 | 8½ R | 7½ L | 6½ R | 10 R | 13 L | 22½ R |
| AKO4A | C | 3/·166 | 0·169 | — | — | 7½ L | — | — | 44½ L | — | — |

### Table 15.

*Conductivity Tests on Single Wires supplied separately* (see Table 1A).

| Maker | Nomiual Diameter of Wire, inch | Resistivity at 20° C., Microhms for a Centimetre Cube | | Percentage relative Mass Conductivity at 20° C. | |
|---|---|---|---|---|---|
| | | Hard | After Annealing | Hard | After Annealing |
| A | 0·104 | $1{\cdot}75_{1}$ | $1{\cdot}71_{8}$ | 98·4 | 100·4 |
| | 0·136 | $1{\cdot}75_{1}$ | $1{\cdot}71_{1}$ | 98·4 | 100·8 |
| | 0·144 | $1{\cdot}74_{5}$ | $1{\cdot}71_{5}$ | 98·8 | 100·5 |
| | 0·166 | $1{\cdot}74_{0}$ | $1{\cdot}71_{1}$ | 99·1 | 100·8 |
| | 0·185 | $1{\cdot}73_{9}$ | $1{\cdot}70_{0}$ | 99·2 | 101·4 |
| | 0·215 | $1{\cdot}73_{9}$ | $1{\cdot}71_{0}$ | 99·2 | 100·8 |
| | Mean .. | $1{\cdot}71_{4}$ | $1{\cdot}71_{1}$ | 98·9 | 100·8 |
| B | 0·104 | $1{\cdot}77_{0}$ | $1{\cdot}70_{8}$ | 98·5 | 101·0 |
| | 0·136 | $1{\cdot}75_{0}$ | $1{\cdot}68_{8}$ | 98·5 | 102·1 |
| | 0·144 | $1{\cdot}76_{2}$ | $1{\cdot}72_{5}$ | 97·9 | 100·0 |
| | 0·166 | $1{\cdot}74_{5}$ | $1{\cdot}70_{4}$ | 98·8 | 101·2 |
| | 0·185 | $1{\cdot}74_{5}$ | $1{\cdot}70_{7}$ | 98·8 | 101·0 |
| | 0·215 | $1{\cdot}75_{6}$ | $1{\cdot}70_{9}$ | 98·2 | 100·9 |
| | Mean .. | $1{\cdot}75_{1}$ | $1{\cdot}70_{7}$ | $98{\cdot}4_{5}$ | 101·0 |
| C | 0·104 | $1{\cdot}76_{5}$ | $1{\cdot}73_{5}$ | 97·7 | 99·4 |
| | 0·136 | $1{\cdot}76_{1}$ | $1{\cdot}72_{2}$ | 97·9 | 100·1 |
| | 0·144 | $1{\cdot}76_{2}$ | $1{\cdot}73_{2}$ | 97·9 | 99·6 |
| | 0·166 | $1{\cdot}76_{2}$ | $1{\cdot}73_{3}$ | 97·9 | 99·5 |
| | 0·185 | $1{\cdot}76_{8}$ | $1{\cdot}73_{2}$ | 97·5 | 99·6 |
| | 0·215 | $1{\cdot}76_{4}$ | $1{\cdot}72_{0}$ | 97·7 | 100·3 |
| | Mean .. | $1{\cdot}76_{4}$ | $1{\cdot}73_{1}$ | 97·8 | 99·75 |

every cable was carried out five times and the modulus of elasticity obtained for each loading. In most cases the load applied during the second and subsequent loadings was above the primitive limit of proportionality. The effect of repeated loading is seen from the results given in Table 13.

## IV. PITCH AND LAY OF CONSTITUENT WIRES OF LONG STRANDED CABLES.

The data given in Table 14 refer to the long stranded cables on which the tensile tests were made :—

Column 1 gives particulars of the cable.

Column 2 gives the mean diameters of the layers of constituent wires ; *a*, *b*, *c* referring to the layers commencing from the outside.

Column 3 gives the measured pitch of the wires.

Column 4 gives the calculated lay where

$$\text{lay} = \frac{\text{measured pitch}}{\text{mean diameter of layer of wires}}$$

NOTE.—The suffixes R and L refer to right-hand and left-hand winding respectively.

## V. CONDUCTIVITY TESTS ON SINGLE WIRES SUPPLIED SEPARATELY.

The wires were tested both in the condition in which they were received and also after they had been annealed.

The values are given in terms of the International Standard of Resistance for Annealed Copper, the standard value for a wire, 1 metre in length, and weighing 1 gramme, being 0·1533 ohm at 20° C.

The results of the tests are given in Table 15.

# REPORT UPON TESTS ON HARD DRAWN ALUMINIUM WIRES AND CABLES FOR OVERHEAD TRANSMISSION LINES.

[Report (Ref. F/T6) received from the British Electrical and Allied Industries Research Association.]

### Contents.

| | Page |
|---|---|
| Introduction | 1013 |
| Scope of Investigation | 1013 |
| Material under Test | 1013 |
| Range of Samples Tested | 1014 |
| Ultimate Tensile Strength | 1014 |
| Extension on Fracture | 1014 |
| Limit of Proportionality | 1014 |
| Modulus of Elasticity | 1015 |
| Twist and Wrap Tests | 1016 |
| Results of Tests | 1017 |
| I. Mechanical Tests on Single Wires supplied separately | 1017 |
| II. Mechanical Tests on Short Stranded Cables | 1019 |
| III. Mechanical Tests on Long Stranded Cables | 1022 |
| IV. Pitch and Lay of Constituent Wires of Long Stranded Cables | 1024 |
| V. Conductivity Tests on Single Wires | 1024 |
| VI. Chemical Analyses of Single Wires supplied separately | 1025 |

Appendix—

A Note on the Resistance Measurement of Aluminium Wire .. .. .. .. 1025

### Introduction.

This report deals with the results of the tests carried out at the National Physical Laboratory on hard drawn aluminium wires and cables, both short and long lengths. The methods employed were similar to those adopted in the tests on hard drawn copper wires and cables, which are described in Technical Report Ref. F/T5.*

### Scope of Investigation.

The physical properties and tests to which special attention was directed were as follows :—

Ultimate tensile strength.
Extension on fracture.
Limit of proportionality.
Modulus of elasticity.
Twist and wrap tests.

### Material under Test.

The material on which the tests, dealt with in the report, were carried out consisted of hard drawn aluminium as furnished for overhead line construction.

Single wires (see Table 1A) were obtained at the same time as the cables (see Table 1B), and purported to be of the same material. This was not borne out in one or two instances by the results obtained. For the purpose of determining the efficiency of the cables a comparison was therefore made also with tests on single wires taken from the individual cables (see Table 10).

Table 1A.

*Single Wires supplied separately.*

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch |
|---|---|---|
| AKM | D | 0·133 |
| | | 0·151 |
| | | 0·167 |
| | | 0·187 |
| | | 0·212 |
| AKP | E | 0·133 |
| | | 0·151 |
| | | 0·167 |
| | | 0·187 |
| | | 0·212 |

Table 1B.

*Stranded Cables.*

| N.P.L. Mark | Maker | Type |
|---|---|---|
| AKM4A | D | 3/·151 |
| AKM4B | D | 7/·151 |
| AKM4C | D | 19/·151 |
| AKM4D | D | 19/·212 |
| AKM4E | D | 37/·208 |
| AKQ4A | E | 3/·151 |
| AKQ4B | E | 7/·151 |
| AKQ4C | E | 19/·151 |
| AKQ4D | E | 19/·212 |
| AKQ4E | E | 37/·208 |
| AUD3 | E | 7/·146 |
| AUD2 | E | 19/·146 |
| AUD1 | E | 37/·146 |

As a considerable difference was noticed in the character of samples supplied by Makers D and E, more particularly in respect of electrical conductivity, analyses were made which indicated a very appreciable difference in purity. Maker D samples showed an average purity of 99·13 per cent and those of Maker E 99·68 per cent. The corresponding conductivities in terms of the annealed copper standard were 57·3 per cent and 61·9 per cent respectively (see Table 15).

---

* See *Journal I.E.E.*, 1923, vol. 61, p. 997.

An explanation of these differences is most probably to be found in the wide variation in the quality of aluminium produced during war-time, and it is considered that the samples supplied by Maker D were most probably drawn from war-time stocks of metal which at the time were still upon the market.

In view of the willingness of aluminium producers to guarantee a conductivity of aluminium wire of 60 per cent of annealed copper, the samples of Maker D cannot be considered as representative, having been manufactured from a material which would not normally be supplied for electrical purposes. On the other hand, the first samples from Maker E were above the usual commercial standard of purity. Additional cables were supplied by Maker E and conductivity tests on the constituent wires showed an average conductivity of 60·8 per cent (see Table 16). It appears that the material of these additional cables may properly be taken as more closely representing present-day practice as to the degree of purity and conductivity of hard drawn aluminium for overhead transmission lines.

### RANGE OF SAMPLES TESTED.

Tests were carried out on single wires of diameters ranging from 0·133 inch to 0·212 inch, and on stranded cables consisting of 3, 7, 19 and 37 wires respectively, the diameters of the wires ranging from 0·146 inch to 0·212 inch.

(*a*) *Single wires supplied separately* (see Table 1A).

Tests were carried out on short lengths (10 inches) of straightened single wire. The tests show close agreement between the behaviour of short lengths of wire and long lengths of cable.

The prevailing practice of determining the physical properties of single wires by tests on short specimens is regarded as satisfactory.

(*b*) *Stranded cables* (see Table 1B).

The tests on short lengths of cable give results which are different from those of tests on long lengths of cable, except in so far as they refer to ultimate strength and on the single wires of which the cables are composed. In short lengths of cable subjected to tension it is apparent that the stress is not shared equally between the wires. The results of tests on short lengths of cable must be rejected on this account, with the exception of the ultimate strength tests.

The tests on long lengths of cables are consistent with one another and (important to note) with tests on the individual straightened wires supplied separately (see Table 12).

### ULTIMATE TENSILE STRENGTH.

The ultimate tensile strengths of the various single wires tested are not in very close agreement.

The generally accepted figure of 11·5 tons per square inch as the breaking stress is not supported by the present tests.

In previous tests on hard drawn wires a fairly definite relationship has been observed between breaking stress and diameter, the strength decreasing as the diameter increases. The present tests show a relationship of the same character, but the results are too irregular to admit of the deduction of figures for the relationship. It is, therefore, advisable to adopt a separate value of the ultimate strength for each size of wire.

The breaking stress of the cables was found, in general, to be less than that of their constituent wires ; this could be accounted for by the assumption of unequal loading of the individual wires.

The strength of a cable in terms of the sum of the strengths of the individual constituent wires was found to vary approximately as follows :—

| | |
|---|---|
| 3 wires .. .. .. | 100 per cent |
| 7 wires .. .. .. | 99 per cent |
| 19 wires .. .. .. | 96 per cent |
| 37 wires .. .. .. | 92 per cent |

The tests showed some inconsistencies, and the ratios of strengths given above should not be regarded as finally proved.

### EXTENSION ON FRACTURE.

The percentage extension on fracture varies with the length of wire tested, and if elongation is to be specified the length of the test specimen must be stated.

The tests show that the percentage extension varies with the diameter of the wire and with the tensile strength. If the results of the tests be grouped in the order of ultimate stress, a relationship is obtained between breaking stress and extension which in general indicates greater elongation with small tensile strength. The relationship is, however, far from definite.

A minimum extension of 4 per cent on a 10-inch gauge length appears to be indicated by the tests.

### LIMIT OF PROPORTIONALITY.

The limit of proportionality between stress and strain is not a physical constant and should therefore have no place in a specification for the material of a wire.

It is advisable, however, that the working stress of overhead wires shall be determined with due regard to the degree of proportionality.

The tests show that the limit of proportionality, though at first much lower than the generally recognized values, increases with repeated loadings. The limits given in Table 12 are those found on a first loading, and in view of the characteristic increase of the limit on repeated loading should not be taken as a basis for deciding the maximum working stress of an overhead wire.

The limit of proportionality corresponding to the higher values of the modulus of elasticity after repeated loadings is not given in the results of the tests.

### Modulus of Elasticity.

The effect of repeated loading to a point beyond the limit of proportionality is to increase the apparent modulus.

Table 2.

*Dimensions of Coils of Single Wire as supplied.*

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Diameter of Coil as received | |
|---|---|---|---|---|
| | | | Internal, inches | External, inches |
| AKM | D | 0·133 | 16·0 | 20·0 |
| | | 0·151 | 16·0 | 20·0 |
| | | 0·167 | 16·0 | 20·5 |
| | | 0·187 | 15·5 | 20·5 |
| | | 0·212 | 16·0 | 20·5 |
| AKP | E | 0·133 | 16·0 | 20·0 |
| | | 0·151 | 15·5 | 20·0 |
| | | 0·167 | 16·0 | 20·5 |
| | | 0·187 | 15·5 | 20·5 |
| | | 0·212 | 16·0 | 20·5 |

On repeated loading the apparent modulus increases towards a maximum value which is the true modulus of the material.

A value of $9 \cdot 6 \times 10^6$ lb. per square inch is indicated by the tests on the long cables, whereas the single wires on the second loading show a very consistent value of $9 \cdot 9 \times 10^6$ lb. per square inch. If, however, the long cables had been loaded as heavily as the single wires the modulus might have been higher.

The three long cables supplied last are more representative, and the value of the modulus given by these cables was $9 \cdot 6 \times 10^6$ lb. per square inch.

A practical point arises from the fact that the true modulus of the material is higher than the value obtained on the first loading. In traction and transmission line work it has been suggested it would be desirable if the wires and cables could have the *true value* of the modulus when *first erected*. If the repeated loadings were applied in the wire-maker's works before coiling on to drums, uncertainty would exist as to the effect of coiling and uncoiling on the final value of the modulus when the wire was strung up on site. Further elongation tests would be necessary to ascertain

Table 3.

*Tensile Strength and Extension of Single Wires supplied separately* (see Table 1a).

| N.P.L. Mark | Maker | Diameter of Wire, inch | Cross-sectional Area of Wire, sq. in. | Breaking Load, tons | Ultimate Stress, tons per sq. inch | Extension on | |
|---|---|---|---|---|---|---|---|
| | | | | | | 10 inches | 2 inches |
| AKM1A | D | 0·134 | 0·0141 | 0·1565 | 11·1 | 0·48 | 0·20 |
| | | | | 0·1600 | 11·35 | 0·48 | 0·18 |
| | | | | 0·1565 | 11·1 | 0·50 | 0·21 |
| AKM1B | D | 0·1518 | 0·0181 | 0·1935 | 10·7 | 0·38 | 0·16 |
| | | | | 0·1925 | 10·6 | 0·48 | 0·19 |
| | | | | 0·1930 | 10·7 | 0·37 | 0·15 |
| AKM1C | D | 0·167 | 0·0219 | 0·2255 | 10·3 | 0·61 | 0·22 |
| | | | | 0·2270 | 10·4 | 0·57 | 0·21 |
| | | | | 0·2225 | 10·2 | 0·50 | 0·22 |
| AKM1D | D | 0·1867 | 0·0274 | 0·2715 | 9·9 | 0·60 | 0·23 |
| | | | | 0·2700 | 9·85 | 0·58 | 0·22 |
| | | | | 0·2730 | 10·0 | 0·55 | 0·22 |
| AKM1E | D | 0·2132 | 0·0357 | 0·3415 | 9·5 | 0·51 | 0·23 |
| | | | | 0·3450 | 9·5 | 0·51 | 0·24 |
| | | | | 0·3335 | 9·35 | 0·48 | 0·22 |
| AKP1A | E | 0·1355 | 0·0144 | 0·1535 | 10·7 | 0·38 | 0·165 |
| | | | | 0·1535 | 10·7 | 0·31 | 0·14 |
| | | | | 0·1550 | 10·8 | 0·36 | 0·16 |
| AKP1B | E | 0·1515 | 0·0180 | 0·1990 | 11·1 | 0·38 | 0·18 |
| | | | | 0·1940 | 10·8 | 0·40 | 0·17 |
| | | | | 0·1945 | 10·8 | 0·33 | 0·18 |
| AKP1C | E | 0·1665 | 0·0218 | 0·2230 | 10·2 | 0·35 | 0·18 |
| | | | | 0·2250 | 10·3 | 0·39 | 0·18 |
| | | | | 0·2210 | 10·1 | 0·37 | 0·18 |
| AKP1D | E | 0·1878 | 0·0277 | 0·2685 | 9·7 | 0·48 | 0·23 |
| | | | | 0·2700 | 9·8 | 0·48 | 0·23 |
| | | | | 0·2770 | 10·0 | 0·47 | 0·22 |
| AKP1E | E | 0·2118 | 0·0352 | 0·3315 | 9·4 | 0·51 | 0·23 |
| | | | | 0·3485 | 9·9 | 0·49 | 0·22 |
| | | | | 0·3330 | 9·5 | 0·63 | 0·25 |

TABLE 4.

*Limits of Proportionality, Modulus and Extension of Single Wires supplied separately* (see Table 1A).

N.P.L. mark, AKM

Maker, D

| | | | | | |
|---|---|---|---|---|---|
| Diameter of wire, inch | 0·1334 | 0·1517 | 0·167 | 0·1867 | 0·213 |
| Cross-sectional area of wire, square inch | 0·01397 | 0·01807 | 0·0209 | 0·02737 | 0·03563 |
| Primitive limit of proportionality, ton | 0·055 | 0·06 | 0·087 | 0·124 | 0·127 |
| Primitive limit of proportionality, tons per square inch | 3·9 | 3·3 | 4·0 | 4·5 | 3·6 |
| Maximum load, ton | 0·149 | 0·1735 | 0·218 | 0·264 | 0·317 |
| Ultimate stress, tons per square inch | 10·7 | 9·6 | 9·95 | 9·65 | 8·9 |
| Modulus (1st), lb. per square inch × $10^{-6}$ | 10·1 | 9·7 | 9·6 | 9·2 | 9·9 |
| Modulus (2nd), lb. per square inch × $10^{-6}$ | 10·1 | 9·9 | 9·9 | 9·8 | 9·9 |
| Extension on 10 in., inch | 0·41 | 0·50 | 0·52 | 0·50 | 0·47 |
| Extension on 2-in., inch | 0·16 | 0·20 | 0·21 | 0·22 | 0·22 |

N.P.L. mark, AKP

Maker, E

| | | | | | |
|---|---|---|---|---|---|
| Diameter of wire, inch | 0·1352 | 0·1517 | 0·1663 | 0·1878 | 0·2117 |
| Cross-sectional area of wire, square inch | 0·01436 | 0·01807 | 0·02172 | 0·0277 | 0·0352 |
| Primitive limit of proportionality, ton | 0·041 | 0·0515 | 0·075 | 0·09 | 0·092 |
| Primitive limit of proportionality, tons per square inch | 2·9 | 2·85 | 3·5 | 3·25 | 2·6 |
| Maximum load, ton | 0·142 | 0·183 | 0·223 | 0·262 | 0·326 |
| Ultimate stress, tons per square inch | 9·9 | 10·1 | 10·3 | 9·5 | 9·3 |
| Modulus (1st), lb. per square inch × $10^{-6}$ | 9·8 | 9·7 | 9·7 | 9·5 | 9·6 |
| Modulus (2nd), lb. per square inch × $10^{-6}$ | 9·9 | 9·05 | 10·1 | 9·8 | 9·7 |
| Extension on 10 in., inch | 0·20 | 0·38 | 0·28 | 0·40 | 0·40 |
| Extension on 2 in., inch | 0·11 | 0·16 | 0·15 | 0·20 | 0·22 |

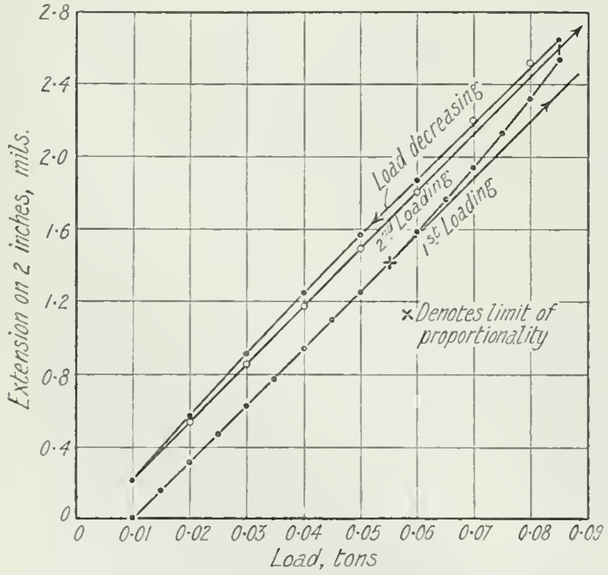


FIG. 1.—Typical Load-extension Curves of Single Wires supplied separately by Maker D.

whether the coiling and uncoiling reduced the modulus from the *true value*.*

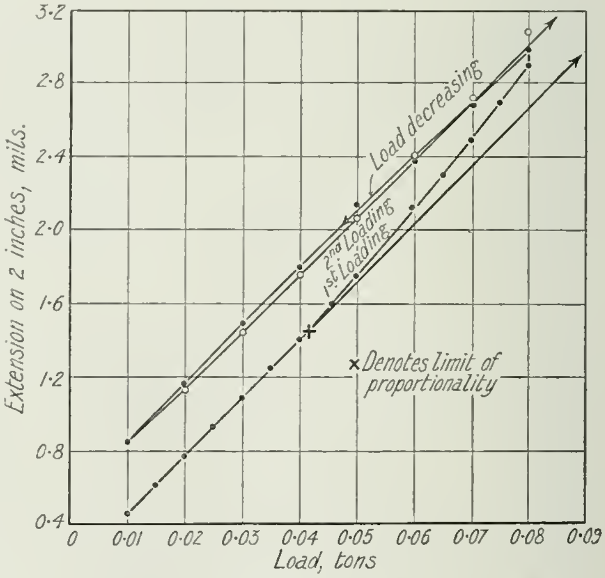


FIG. 2.—Typical Load-extension Curves of Single Wires supplied separately by Maker E.

TWIST AND WRAP TESTS.

The results of these tests show no direct relationship to the percentage elongation referred to above. The tests are of interest, but there is not sufficient evidence to show that the specification of such tests is of more than general value.

---

* The wire-makers on the Sub-Committee have stated that it would be impracticable to carry out the repeated loadings at the manufacturer's works.

It should be borne in mind, however, that twist and wrap tests can be carried out so easily that wire-makers prefer these tests to extension tests.

## RESULTS OF TESTS.

Details of the methods of test employed at the N.P.L. are given in Technical Report Reference F/T5.

TABLE 5.

*Twist Tests on Single Wires supplied separately* (see Table 1A).

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Number of Twists on 6-in. Length | 6-in. Length (Repeat) | 3-in. Length |
|---|---|---|---|---|---|
| AKM2A | D | 0·133 | 42 | — | 40 |
| | | | 45 | — | 39 |
| | | | 42 | — | 38½ |
| AKM2B | D | 0·151 | 41 | — | — |
| | | | 42½ | — | — |
| | | | 41½ | — | — |
| AKM2C | D | 0·167 | 39 | — | — |
| | | | 43 | — | — |
| | | | 43 | — | — |
| AKM2D | D | 0·187 | 41 | — | — |
| | | | 44 | — | — |
| | | | 46 | — | — |
| AKM2E | D | 0·212 | 35 | — | — |
| | | | 37½ | — | — |
| | | | 40 | — | — |
| AKP2A | E | 0·133 | 22½ | 22 | 15 |
| | | | 21 | 23 | 14½ |
| | | | 24 | 23 | 14 |
| AKP2B | E | 0·151 | 21 | — | 10 |
| | | | 21½ | — | 10 |
| | | | 20 | — | 11½ |
| AKP2C | E | 0·167 | 18½ | — | — |
| | | | 19 | — | — |
| | | | 20 | — | — |
| AKP2D | E | 0·187 | 23½ | — | — |
| | | | 21½ | -- | — |
| | | | 22 | — | — |
| AKP2E | E | 0·212 | 22 | — | — |
| | | | 23½ | — | — |
| | | | 22½ | — | — |

The results of the tests on the aluminium wires and cables are given on the following pages.*

## I. MECHANICAL TESTS ON SINGLE WIRES SUPPLIED SEPARATELY.

The samples of single wire were supplied in the form of coils, the dimensions of which are given in Table 2.

### DETERMINATION OF BREAKING LOAD.

The results of the tensile strength tests, in general, on three samples of each wire are given in Table 3. All the test pieces from each coil were cut from the sample end, and were not straightened before test. The air temperature was about 22° C. in every case. The breaking load was ascertained by applying 9/10 of the load in 5 seconds and the remaining 1/10 in 5 seconds.

TABLE 6.

*Wrap Tests on Single Wires supplied separately* (see Table 1A).

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Statement of Results |
|---|---|---|---|
| AKM3A | D | 0·133 | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 2 |
| AKM3B | D | 0·151 | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 1 |
| AKM3C | D | 0·167 | 9, 6, 6, 6, 6, 6, 2 |
| | | | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 1 |
| AKM3D | D | 0·187 | 9, 6, 6, 6, 6, 6, 6, 2 |
| | | | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 3 |
| AKM3E | D | 0·212 | 12, 6, 6, 6, 6, 6, 6, 6 |
| | | | 12, 6, 6, 6, 6 6, 6, 5 |
| | | | 12, 6, 6, 6, 6, 6, 6, 2 |
| AKP3A | E | 0·133 | 9, 6, 6, 6, 6, 6, 6, 3 |
| | | | 9, 6, 6, 6, 6, 6, 6, 2 |
| | | | 9, 6, 6, 6, 6, 6, 6, 4 |
| AKP3B | E | 0·151 | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 4 |
| AKP3C | E | 0·167 | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 1 |
| | | | 9, 6, 6, 6, 6, 6, 6, 2 |
| AKP3D | E | 0·187 | 9, 6, 6, 6, 6, 2 |
| | | | 9, 6, 6, 6, 6, 6, 6, 3 |
| | | | 9, 6, 6, 6, 6, 6, 6, 5 |
| AKP3E | E | 0·212 | 12, 6, 6, 6, 6, 6, 6, 1 |
| | | | 12, 6, 6, 6, 6, 6, 6, 1 |
| | | | 12, 6, 6, 6, 6, 6, 6, 1 |

### DETERMINATION OF THE LIMIT OF PROPORTIONALITY, MODULUS, AND EXTENSION.

Tensile tests were made on straightened lengths of wire having 10 inches between the grips. The extension on a 2-inch middle portion of the wire was measured by means of a Marten's mirror extensometer. The primitive limit of proportionality and the modulus at first loading were obtained by loading up in steps to a point just beyond the limit of proportionality. The load was then removed, and a second modulus obtained by again loading up to the same point.

The results are given in Table 4.

---

* The original Report was accompanied by drawings showing the apparatus used. These can be inspected at the E.R.A. office.

### TABLE 7.

*Summary of Results of Tests on Single Wires supplied separately* (see Table 1A).

| Nominal Diameter of Wire, inch | Primitive Limit of Proportionality, tons per sq. in. | Ultimate Stress |  | Extension, inch |  |  |  | Modulus of Elasticity, lb. per sq. in. × 10⁻⁶ |  | Average Twists on |  | Minimum Value for Wrap Test | Relative Conductivity at 20° C. | Percentage of Aluminium in Wire |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Slow Loading, tons per sq. in. | Quick Loading, tons per sq. in. | Slow Loading on |  | Quick Loading on |  |  |  |  |  |  |  |  |
|  |  |  |  | 10 in. | 2 in. | 10 in. | 2 in. | 1st | 2nd | 6 in. | 3 in. |  |  |  |
|  |  |  |  | N.P.L. Mark, AKM |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  | Maker, D |  |  |  |  |  |  |  |  |  |  |
| 0·133 | 3·9 | 10·7 | 11·2 | 0·41 | 0·16 | 0·49 | 0·19 | 10·1 | 10·1 | 43 | 39 | 9, 6, 6, 6, 6, 6, 6 | 57·4 | — |
| 0·151 | 3·3 | 9·6 | 10·6 | 0·50 | 0·20 | 0·41 | 0·17 | 9·7 | 9·9 | 42 | — | 9, 6, 6, 6, 6, 6, 6 | 57·8 | 99·11 |
| 0·167 | 4·0 | 9·95 | 10·3 | 0·52 | 0·21 | 0·56 | 0·22 | 9·6 | 9·9 | 42 | — | 9, 6, 6, 6, 6, 6 | 57·0 | — |
| 0·187 | 4·5 | 9·65 | 9·9 | 0·50 | 0·22 | 0·58 | 0·22 | 9·2 | 9·8 | 44 | — | 9, 6, 6, 6, 6, 6, 6 | 57·0 | — |
| 0·212 | 3·6 | 8·9 | 9·5 | 0·47 | 0·22 | 0·50 | 0·23 | 9·9 | 9·9 | 38 | — | 12, 6, 6, 6, 6, 6, 6 | 57·1 | 99·14 |
|  |  |  |  | N.P.L. Mark, AKP |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  | Maker, E |  |  |  |  |  |  |  |  |  |  |
| 0·133 | 2·9 | 9·9 | 10·7 | 0·20 | 0·11 | 0·35 | 0·16 | 9·8 | 9·9 | 23 | 15 | 9, 6, 6, 6, 6, 6, 6 | 61·6 | — |
| 0·151 | 2·85 | 10·1 | 10·9 | 0·38 | 0·16 | 0·37 | 0·18 | 9·7 | 9·95 | 21 | 11 | 9, 6, 6, 6, 6, 6, 6 | 61·7 | 99·67 |
| 0·167 | 3·5 | 10·3 | 10·2 | 0·28 | 0·15 | 0·37 | 0·18 | 9·7 | 10·1 | 19 | — | 9, 6, 6, 6, 6, 6, 6 | 61·8 | — |
| 0·187 | 3·25 | 9·5 | 9·8 | 0·40 | 0·20 | 0·48 | 0·23 | 9·5 | 9·8 | 22 | — | 9, 6, 6, 6, 6 | 62·2 | — |
| 0·212 | 2·6 | 9·3 | 9·6 | 0·40 | 0·22 | 0·44 | 0·23 | 9·6 | 9·7 | 23 | — | 12, 6, 6, 6, 6, 6, 6 | 62·2 | 99·69 |

It was found that a straight elastic line, and, therefore, the limit of proportionality, could not be obtained by tests made on bent wires, so that all the wires had to be straightened before test. Figs. 1 and 2 give the results of typical tests on wires previously straightened.

It will be noted that the values of the limit of proportionality are much lower than the generally recognized values. They are the loads or stresses at which the first deviations from Hooke's Law were observed upon the first loading of the wires. The values of these limits of proportionality depend, to a large extent, upon the accuracy with which the strains can be observed, and it may be assumed that, in general, the lower the accuracy the higher will be the value of the apparent limit of proportionality.

The value of the primitive limit of proportionality is not of very great importance. If the wire is reloaded after the limit of proportionality has been exceeded a new and higher value of the limit is obtained, the amount of the increase depending on the amount by which the primitive limit of proportionality has been exceeded.

The maximum load was also obtained during these tests and the results are given in Table 4. The final 1/10 of the load was applied in approximately two minutes, and the results are referred to subsequently as "slow loading tests" (see Tables 7 and 10).

### TWIST TESTS.

The wires were straightened before test, and were cut from the same end of the coil as the tensile test pieces. The distance between the jaws was set at 6 inches for all the samples, but additional tests on 3-inch lengths were made on the small diameter wires.

The results of these tests are given in Table 5.

### WRAP TESTS.

The British Engineering Standards Association Specification for hard drawn copper wire states that "the test sample shall be closely lapped six times round wire of its own diameter, unlapped, and again closely lapped round wire of its own diameter in the same direction as the first lapping without breaking."

Tests were made on these lines, but the wrapping and unwrapping was continued until fracture occurred. It was found necessary to wrap on 9 or 12 turns in the first wrapping, and then wrap and unwrap 6 turns as required in the test, so as to make the unwrapping operation easier during the last few turns.

The results of these tests are given in Table 6. In this table the results are stated in the following form—the 1st, 3rd, 5th, etc., numbers represent the wrapping operation, the intermediate numbers the unwrapping operation.

### SUMMARY OF RESULTS.

The results given in the previous tables have been summarized in Table 7, average values being given in place of the full detail results, and the relative conductivity at 20° C. and the percentage of aluminium have also been included.

## II. MECHANICAL TESTS ON SHORT STRANDED CABLES.

Details of the stranded cables on which the tests were carried out are given in Table 8.

### DETERMINATION OF BREAKING LOAD.

*Strength of constituent wires of the cables.*—To determine the efficiencies of the cables, it was originally intended to compare the breaking stress of the cable with the results of the tests on single wires. Preliminary tests showed, however, that great differences existed between the stated and the actual tensile strengths of the constituent wires of the cables. One cable (advised as 7-strand aluminium) proved to have a steel core. It was also found that up to as much as 25 per cent difference in tensile strength existed between individual wires of the same cable. It was decided, therefore, to determine the breaking load of all the constituent wires of the cables.

TABLE 8.

*Stranded Cables.*

| N.P.L. Mark | Maker | Type | Diameter of Cable, inches |
|---|---|---|---|
| AKM4A | D | 3/·151 | 0·28 |
| AKM4B | D | 7/·151 | 0·31 |
| AKM4C | D | 19/·151 | 0·75 |
| AKM4D | D | 19/·212 | 1·06 |
| AKM4E | D | 37/·208 | 1·44 |
| AKQ4A | E | 3/·151 | 0·28 |
| AKQ4B | E | 7/·151 | 0·31 |
| AKQ4C | E | 19/·151 | 0·75 |
| AKQ4D | E | 19/·212 | 1·06 |
| AKQ4E | E | 37/·208 | 1·44 |
| AUD3 | E | 7/·146 | 0·44 |
| AUD2 | E | 19/·146 | 0·72 |
| AUD1 | E | 37/·146 | 1·02 |

*Extension at fracture.*—Gauge marks, 8 inches apart, were made on the cable at the commencement of the tests. In many cases the cable unstranded in the vicinity of the fracture and it was found impossible to measure the extension. In the majority of cases, corresponding ends of broken wires were misplaced and it was extremely difficult to place the fractured ends in their true relative positions. The measured extensions are, therefore, given chiefly for their relative values. The accuracy of their values cannot be relied upon.

*Conditions of tests.*—The length of cable between the grips was 14 inches. The tests on the cables were carried out as nearly as possible in conformity with the British Engineering Standards Association Specification for hard drawn copper wire, viz. 9/10 of the breaking load was applied in 5 seconds and the remaining 1/10 in 5 seconds. The latter condition was not always fulfilled, as, usually, after the apparent maximum load had been applied and the beam of the testing machine began to fall, the cable seemed to recover, and further load had to be applied. The results of tests to fracture on the cables and constituent wires are given in Table 9.

Table 10 gives the collected results of the breaking stresses of the short lengths of cables and compares them with the total strength of their constituent wires and also the results of the single wire tests.

Column 1 gives particulars of the cables and their ultimate stresses.

Column 2 gives the ultimate stress of the constituent wires.

Column 3 is a summary of the single-wire tests. The values obtained for slow and quick loading are inserted.

Column 4 gives the percentage strength of the cable as compared with that of the constituent wires, so that

TABLE 9.

*Tensile Strength of Short Cables and of Constituent Wires.*

| N.P.L. Mark | Maker | Type | Cable | | | | Constituent Wires | |
|---|---|---|---|---|---|---|---|---|
| | | | Cross-sectional Area, sq. in. | Breaking Load, tons | Ultimate Stress, tons/in.$^2$ | Per cent Extension on 8 inches | Total Breaking Load, tons | Ultimate Stress, tons/in.$^2$ |
| AKM4A | D | 3/·151 | 0·0535 | 0·56 | 10·5 | 4 | 0·56 | 10·5 |
| AKM4B | D | 7/·151 | 0·1254 | 1·40 | 11·2 | 4 | 1·38 | 11·0 |
| AKM4C | D | 19/·151 | 0·3330 | 3·55 | 10·7 | 2 | 3·71 | 11·1 |
| AKM4D | D | 19/·212 | 0·6607 | 6·65 | 10·1 | 2 | 6·82 | 10·3 |
| AKM4E | D | 37/·208 | 1·241 | 11·65 | 9·4 | 2 | 12·6 | 10·2 |
| AKQ4A | E | 3/·151 | 0·0544 | 0·61 | 11·2 | 4 | 0·61 | 11·2 |
| AKQ4B | E | 7/·151 | 0·1255 | 1·35 | 10·8 | 4 | 1·41 | 11·2 |
| AKQ4C | E | 19/·151 | 0·3359 | 3·74 | 11·1 | 3 | 3·96 | 11·8 |
| AKQ4D | E | 19/·212 | 0·6647 | 6·48 | 9·8 | 3 | 6·84 | 10·3 |
| AKQ4E | E | 37/·208 | 1·231 | 11·2 | 9·10 | 2 | 12·2 | 9·9 |

TABLE 10.

*Tensile Strength of Short Cables and their Constituent Wires and of Single Wires supplied separately.*

| Column 1 | | | | Column 2 | Column 3 | | | | Column 4 | Column 5 | Column 6 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tests on Short Cables | | | | Tests on Constituent Wires, Ultimate Stress of Wires Forming Cable, tons/in.$^2$ | Tests on Single Wires supplied separately | | | | Efficiency on Constituent Wires, per cent | Efficiency on Single Wire, Slow Loading, per cent | Efficiency on Single Wire, Quick Loading, per cent |
| N.P.L. Mark | Maker | Type | Ultimate Stress of Cable, tons/in.$^2$ | | Maker | Diameter, in. | Ultimate Stress tons/in.$^2$ | | | | |
| | | | | | | | Slow Loading | Quick Loading | | | |
| AKM4A | D | 3/·151 | 10·5 | 10·5 | D | 0·151 | 9·6 | 10·6 | 100 | 109 | 99 |
| AKM4B | D | 7/·151 | 11·2 | 11·0 | D | 0·151 | 9·6 | 10·6 | 102 | 117 | 106 |
| AKM4C | D | 19/·151 | 10·7 | 11·1 | D | 0·151 | 9·6 | 10·6 | 96 | 111 | 101 |
| AKM4D | D | 19/·212 | 10·1 | 10·3 | D | 0·212 | 8·9 | 9·5 | 98 | 113 | 106 |
| AKM4E | D | 37/·208 | 9·4 | 10·2 | D | 0·212 | 8·9 | 9·5 | 92 | 106 | 99 |
| AKQ4A | E | 3/·151 | 11·2 | 11·2 | E | 0·151 | 10·1 | 10·9 | 100 | 111 | 103 |
| AKQ4B | E | 7/·151 | 10·8 | 11·2 | E | 0·151 | 10·1 | 10·9 | 96 | 107 | 99 |
| AKQ4C | E | 19/·151 | 11·1 | 11·8 | E | 0·151 | 10·1 | 10·9 | 94 | 110 | 102 |
| AKQ4D | E | 19/·212 | 9·8 | 10·3 | E | 0·212 | 9·3 | 9·6 | 95 | 105 | 102 |
| AKQ4E | E | 37/·208 | 9·1 | 9·9 | E | 0·212 | 9·3 | 9·6 | 92 | 98 | 95 |

Efficiency on constituent wires, per cent

$$= \frac{\text{Ultimate strength of cable (tons per sq. in.)}}{\text{Total ultimate strength of constituent wires (tons per sq. in.)}} \times 100$$

TABLE 11.

*Limit of Proportionality and Young's Modulus for Short Cables and for Single Wires supplied separately.*

| Tests on Short Cables | | | | | | | | | | | | | Tests on Single Wires supplied separately | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N.P.L. Mark | Maker | Type | Cross-sectional Area, sq. in. | Primitive Limit of Proportionality | | Modulus ($E$), lb./in.$^2$ × 10$^{-6}$ | | | | | | Maker | Diameter, in. | Stress at Limit of Proportionality, tons/in.$^2$ | Modulus ($E$), lb./in.$^2$ × 10$^{-6}$ | |
| | | | | Load, tons | Stress, tons/in.$^2$ | 1st | 2nd | 3rd | 4th | 5th | 10th | | | | 1st | 2nd |
| AKM4A | D | 3/·151 | 0·0535 | 0·19 | 3·6 | 5·4 | 7·0 | — | — | — | — | D | 0·151 | 3·3 | 9·7 | 9·9 |
| AKM4B | D | 7/·151 | 0·1254 | 0·62 | 4·9 | 6·9 | 9·0 | — | — | — | — | D | 0·151 | 3·3 | 9·7 | 9·9 |
| AKM4C | D | 19/·151 | 0·3330 | 0·65 | 2·0 | 4·8 | 6·2 | 6·2 | 6·2 | 6·2 | 6·2 | D | 0·151 | 3·3 | 9·7 | 9·9 |
| AKM4D | D | 19/·212 | 0·6607 | 3·20 | 4·8 | 5·4 | 8·3 | 7·8 | 7·9 | 7·9 | 7·9 | D | 0·212 | 3·6 | 9·9 | 9·9 |
| AKM4E | D | 37/·208 | 1·241 | 4·5 | 3·6 | 2·6 | 5·6 | 6·9 | 7·0 | 7·1 | 7·1 | D | 0·212 | 3·6 | 9·9 | 9·9 |
| AKQ4A | E | 3/·151 | 0·0544 | 0·16 | 2·9 | 7·3 | 7·9 | — | — | — | — | E | 0·151 | 2·8 | 9·7 | 9·9 |
| AKQ4B | E | 7/·151 | 0·1255 | 0·37 | 3·0 | 6·7 | 8·7 | — | — | — | — | E | 0·151 | 2·8 | 9·7 | 9·9 |
| AKQ4C | E | 19/·151 | 0·3359 | 0·85 | 2·5 | 5·2 | 8·3 | 8·8 | 8·8 | 8·8 | 8·9 | E | 0·151 | 2·8 | 9·7 | 9·9 |
| AKQ4D | E | 19/·212 | 0·6647 | 2·0 | 3·0 | 3·8 | 5·5 | 6·0 | 7·5 | 7·3 | 7·3 | E | 0·212 | 2·6 | 9·6 | 9·7 |
| AKQ4E | E | 37/·208 | 1·231 | 3·0 | 2·4 | 2·4 | 6·6 | 6·9 | 7·0 | 7·1 | 7·1 | E | 0·212 | 2·6 | 9·6 | 9·7 |

Columns 5 and 6 give the percentage strength of the cable as compared with the results obtained on the single wire tests.

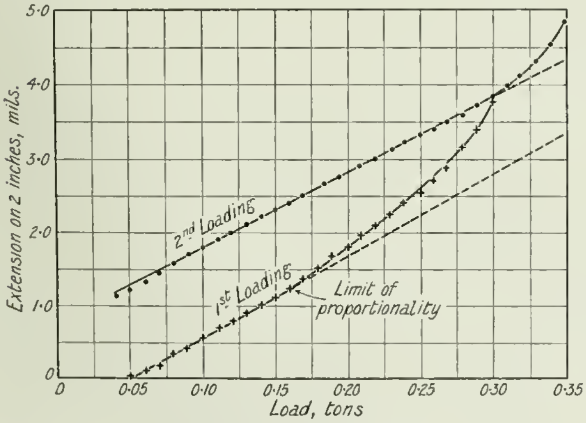


FIG. 3.—Typical Load-extension Curves of Small Short Stranded Cables (3/·151).

Efficiency on single wire, per cent

$$= \frac{\text{Ultimate strength of cable (tons per sq. in.)}}{\text{Ultimate strength of single wire (tons per sq. in.)}} \times 100$$

## DETERMINATION OF THE LIMIT OF PROPORTIONALITY AND MODULUS.

The length of cable under test between the edges of the grips, was 14 inches. A Ewing extensometer was used to measure the strains which were observed on a length of 8 inches. The primitive limit of proportionality and the modulus, at first loading, were obtained by loading up in equal steps to a point just beyond the load where the limit of proportionality was observed. The load was then removed and a second modulus obtained by loading up again to the same point.

It will be noted that the strains thus obtained were those due to the outside wires only while the corresponding stresses were calculated for the total area of the cable under test. After a number of cables had been tested, a comparison of the results obtained with those of the single wire tests showed great differences. In nearly every case the limit of proportionality and the value of Young's Modulus obtained for the cable were much higher and lower respectively than those obtained for the single wires. At the same time the regularity of the plotted points shows that the results obtained are the true strains for the outside wires and indicates that the stress distribution across

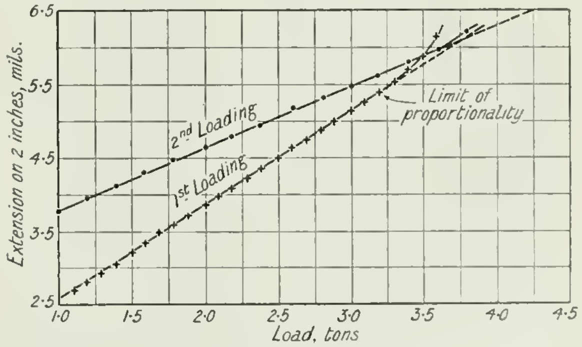


FIG. 4.—Typical Load-extension Curves of Large Short Stranded Cables (19/·212).

TABLE 12.

*Limit of Proportionality and Young's Modulus for 100-yard Lengths of Cables.*

| N.P.L. mark | AKM4B | AKM4C | AKM4E | AUD3 | AUD2 | AUD1 |
|---|---|---|---|---|---|---|
| Maker | D | D | D | E | E | E |
| Type | 7/·151 | 19/·151 | 37/·208 | 7/·146 | 19/·146 | 37/·146 |
| Area, square inches | 0·1254 | 0·333 | 1·241 | 0·114 | 0·314 | 0·611 |
| Load at limit of proportionality, tons | 0·36 | 0·73 | — | 0·476 | 1·13 | — |
| Stress at limit of proportionality, tons per sq. inch | 2·85 | 2·2 | — | 4·18 | 3·6 | — |
| Modulus ($E$), lb. per square inch $\times 10^{-6}$ :— | | | | | | |
| 1st loading | 9·2 | 8·2 | 7·2 | 8·9 | 7·3 | 8·4 |
| 2nd ,, | 9·2 | 9·1 | 8·0 | 9·8 | 9·2 | 9·0 |
| 3rd ,, | 9·0 | 8·8 | 8·3 | 9·8 | 9·8 | 9·5 |
| 4th ,, | 9·2 | 9·6 | 8·6 | 9·6 | 9·3 | 9·6 |
| 5th ,, | 9·0 | 9·6 | 9·0 | 9·6 | 9·4 | 9·6 |
| Temperature during test, ° C. | 11½ | 9 | 9 | 9 | 10 | 5 |
| | *Tests on single wires supplied separately for comparison.* | | | | | |
| Maker | D | D | D | No tests have been made on the constituent wires on short lengths of these cables | | |
| Diameter, inch | 0·151 | 0·151 | 0·212 | | | |
| Stress at limit of proportionality, tons per sq. inch | 3·3 | 3·3 | 3·6 | | | |
| Modulus ($E$), lb. per square inch $\times 10^{-6}$ :— | | | | | | |
| 1st loading | 9·7 | 9·7 | 9·9 | | | |
| 2nd ,, | 9·9 | 9·9 | 9·9 | | | |

the cable is not uniform. It was thought that if the loading were repeated a sufficient number of times, the value obtained for the modulus would, perhaps, tend to approach the true value for the material of which the cable was composed. Accordingly for the remainder of the cables the modulus was determined for the first, second, third, fourth, fifth and tenth loadings. The results show that the modulus under successive loadings tended to approach a limiting maximum value, but in the majority of cables tested this limiting value was much below the true value of the material of which the cable was composed.

The results of the tests on long lengths of cable reveal some interesting facts on this point and seem to indicate that the value of the limit of proportionality and modulus obtained by tensile tests on short lengths of cables, are unreliable and inaccurate.

*Results.*—Table 11 gives the values obtained on short lengths of cable for the limit of proportionality and Young's Modulus under successive loadings. The results of similar tests on the single wires supplied separately are included for purposes of comparison.

Representative load-extension curves obtained are shown on Figs. 3 and 4.

## III. MECHANICAL TESTS ON LONG STRANDED CABLES.

Details of the stranded cables on which the tests were carried out are given in Table 8 in Section II. The test required was the determination of Young's Modulus ($E$) under tensile loading employing a test length of 100 yards.

In the first instance three cables were selected for the tests on the 100-yard lengths. On the completion of these tests three further cables were tested in a similar manner.

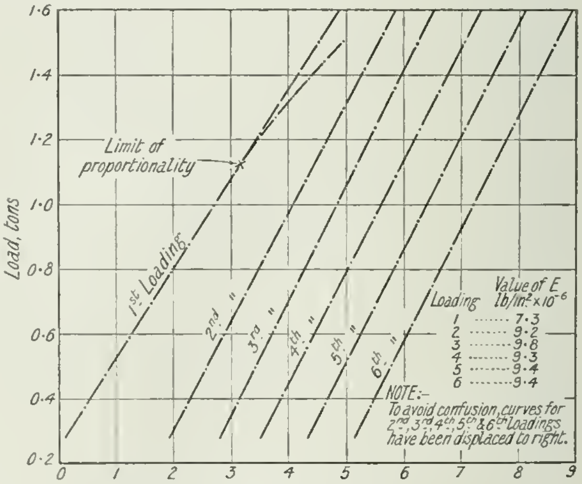


FIG. 5.—Typical Load-extension Curves of 100-yard Lengths of Cables (19/·144).

The tests were carried out as described in Technical Report upon Tests on Hard Drawn Copper Wires and Cables for Overhead Transmission Lines, Ref. F/T5.

## Table 13.

*Alteration of Modulus of 100-yard Lengths of Cables by Repeated Loadings.*

| N.P.L. Mark | Maker | Type of Cable | Modulus of Elasticity, lb. per sq. in. | | Ratio $\frac{A}{B}$, per cent | Percentage of Breaking Load applied |
|---|---|---|---|---|---|---|
| | | | A<br>1st Loading | B<br>5th Loading | | |
| AKM4 | D | 7/·151 | $9{\cdot}2 \times 10^6$ | $9{\cdot}2 \times 10^6$ | 100 | 32 |
| AKM4 | D | 19/·151 | $8{\cdot}2 \times 10^6$ | $9{\cdot}6 \times 10^6$ | 85 | 32 |
| AKM4 | D | 37/·208 | $7{\cdot}2 \times 10^6$ | $9{\cdot}0 \times 10^6$ | 80 | 32 |
| AUD3 | E | 7/·146 | $8{\cdot}9 \times 10^6$ | $9{\cdot}6 \times 10^6$ | 93 | — |
| AUD2 | E | 19/·146 | $7{\cdot}3 \times 10^6$ | $9{\cdot}4 \times 10^6$ | 78 | — |
| AUD1 | E | 37/·146 | $8{\cdot}4 \times 10^6$ | $9{\cdot}6 \times 10^6$ | 87 | — |

## Table 14.

*Pitch and Lay of Constituent Wires of 100-yard Lengths of Cables.*

| Column 1 | | | Column 2 | | | Column 3 | | | Column 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N.P.L. Mark | Maker | Type of Cable | Measured Pitch Diameter, in. | | | Measured Pitch of Wires, in. | | | Lay of Wires | | |
| | | | $a$ | $b$ | $c$ | $A$ | $B$ | $C$ | $\frac{A}{a}$ | $\frac{B}{b}$ | $\frac{C}{c}$ |
| AKM4B | D | 7/·151 | 0·304 | — | — | 6¼ R | — | — | 20½ R | — | — |
| AKM4C | D | 19/·151 | 0·599 | 0·299 | — | 8½ R | 10 L | — | 14 R | 33½ L | — |
| AKM4E | D | 37/·208 | 1·242 | 0·817 | 0·417 | 19 R | 19 L | 8 R | 15½ R | 23½ L | 19 R |
| AUD3 | E | 7/·144 | 0·291 | — | — | 6 L | — | — | 20½ L | — | — |
| AUD2 | E | 19/·144 | 0·586 | 0·291 | — | 9 R | 6 L | — | 15½ R | 20½ L | — |
| AUD1 | E | 37/·144 | 0·881 | 0·581 | 0·291 | 11½ L | 8½ R | 6 L | 13 L | 14½ R | 20½ L |

## Table 15.

*Conductivity Tests on Single Wires supplied separately.*

| Maker | Nominal Diameter of Wire, inch | Resistivity at 20° C. Microhms for a Centimetre Cube | | Percentage Relative Conductivity at 20° C. compared with Annealed Copper of | | | |
|---|---|---|---|---|---|---|---|
| | | | | Equal Mass | | Equal Volume | |
| | | Hard | After Annealing | Hard | After Annealing | Hard | After Annealing |
| D | 0·133 | $3{\cdot}00_1$ | *$3{\cdot}09_6$ | 188·5 | *182·7 | 57·4 | *55·8 |
| | 0·151 | $2{\cdot}98_5$ | $2{\cdot}90_4$ | 189·5 | 194·8 | 57·8 | 59·4 |
| | 0·167 | $3{\cdot}02_6$ | $3{\cdot}00_2$ | 187·0 | 188·4 | 57·0 | 57·5 |
| | 0·187 | $3{\cdot}02_6$ | $2{\cdot}97_7$ | 187·0 | 190·0 | 57·0 | 58·0 |
| | 0·212 | $3{\cdot}02_1$ | $2{\cdot}95_9$ | 187·3 | 191·2 | 57·1 | 58·4 |
| | Mean | $3{\cdot}01_2$ | †$2{\cdot}96_0$ | 187·9 | †191·1 | 57·3 | †58·3 |
| E | 0·133 | $2{\cdot}79_8$ | $2{\cdot}77_7$ | 202·2 | 203·7 | 61·6 | 62·1 |
| | 0·151 | $2{\cdot}79_4$ | $2{\cdot}76_3$ | 202·5 | 204·8 | 61·7 | 62·4 |
| | 0·167 | $2{\cdot}78_9$ | $2{\cdot}71_0$ | 202·8 | 208·7 | 61·8 | 63·7 |
| | 0·187 | $2{\cdot}77_3$ | $2{\cdot}74_4$ | 204·0 | 206·2 | 62·2 | 62·9 |
| | 0·212 | $2{\cdot}77_3$ | $2{\cdot}69_8$ | 204·0 | 209·7 | 62·2 | 64·0 |
| | Mean | $2{\cdot}78_5$ | $2{\cdot}73_8$ | 203·1 | 206·6 | 61·9 | 63·0 |

* This wire was apparently overheated in annealing and the result is, therefore, not reliable.

† In computing the mean the first value has been discarded.

The results of the tests are given in Table 12. For purposes of comparison, the limit of proportionality and modulus obtained from the tests on single wires are included.

There was a kink in cable AUD1, and to remove it a preliminary stress of 4·6 tons per square inch was applied to the cable for two days. On subsequent loading, a limit of proportionality appeared at this stress. The primitive limit of proportionality was, therefore, either at or below this value (4·6 tons per square inch).

A typical load-extension diagram is shown in Fig. 5. To ascertain the amount of increase of the modulus of elasticity due to repeated loadings, the loading of the cables was carried out five times, and the modulus of elasticity obtained for each loading. In most cases the load applied during the second and subsequent loadings was above the primitive limit of proportionality. The effect of repeated loading is seen from the results given in Table 13.

## IV. PITCH AND LAY OF CONSTITUENT WIRES OF LONG STRANDED CABLES.

The data given in Table 14 refers to the long stranded cables on which the tensile tests were carried out :—

Column 1 gives particulars of the cable.

Column 2 gives the mean diameters of the layers of constituent wires ; *a*, *b*, *c* referring to the layers commencing from the outside.

Column 3 gives the measured pitch of the strands

Column 4 gives the calculated lay where

$$\text{lay} = \frac{\text{measured pitch}}{\text{mean diameter of layer of wires}}$$

NOTE.—The suffixes R and L refer to right-hand and left-hand winding respectively.

TABLE 16.

*Conductivity Tests on Constituent Wires of Cables.*

| N.P.L. Mark | Maker | Type | Position in Cable of Wire | N.P.L. Mark for Wire | Resistivity at 20° C. Microhms for a Centimetre Cube | Percentage Relative Conductivity at 20° C. compared with Annealed Copper of | |
|---|---|---|---|---|---|---|---|
| | | | | | | Equal Mass | Equal Volume |
| AUD1 | E | 37/·146 | Core | AUD1*a* | $2\cdot83_9$ | 199·3 | 60·7 |
| | | | 2nd layer | AUD1*b* | $2\cdot84_5$ | 198·8 | 60·6 |
| | | | 3rd layer | AUD1*c* | $2\cdot82_3$ | 200·4 | 61·1 |
| AUD2 | E | 19/·146 | Core | AUD2*a* | $2\cdot84_2$ | 199·1 | 60·7 |
| | | | 1st layer | AUD2*b* | $2\cdot83_1$ | 199·8 | 60·9 |
| | | | 2nd layer | AUD2*c* | $2\cdot83_6$ | 199·5 | 60·8 |
| AUD3 | E | 7/·146 | Core | AUD3*a* | $2\cdot83_9$ | 199·3 | 60·7 |
| | | | 1st layer | AUD3*b* | $2\cdot83_0$ | 199·9 | 60·9 |
| | | | 1st layer | AUD3*c* | $2\cdot83_6$ | 199·5 | 60·8 |

TABLE 17.

*Chemical Analyses of Single Wires supplied separately* (see Table 1A).

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Silicon, per cent | Iron, per cent | Copper | Aluminium, per cent (by difference) |
|---|---|---|---|---|---|---|
| MO186 | D | 0·151 | 0·44 | 0·45 | trace | 99·11 |
| MO187 | D | 0·212 | 0·43 | 0·43 | trace | 99·14 |
| MO188 | E | 0·151 | 0·18 | 0·15 | trace | 99·67 |
| MO189 | E | 0·212 | 0·17 | 0·14 | trace | 99·69 |

## V. CONDUCTIVITY TESTS ON SINGLE WIRES.

Single wires supplied separately by Makers D and E were tested both in the condition in which they were received and also after they had been annealed.

The values are given in terms of the International Standard of Resistance for Annealed Copper, the standard value for a wire, 1 metre in length, and weighing 1 gramme, being 0·1533 ohm at 20° C.

The results of the tests are given in Table 15.

Conductivity tests were also carried out on wires taken from the second set of aluminium cables supplied by Maker E. Three wires were taken from each cable.

Table 16 gives the results obtained together with the position in the cable of the wires tested. The layers of wires are numbered from the core outwards. The density of the aluminium was assumed to be 2·71. The wires were tested as received.

## VI. CHEMICAL ANALYSES OF SINGLE WIRES SUPPLIED SEPARATELY.

Four samples of single wire were submitted to chemical analyses and the results are given in Table 17.

## APPENDIX.

### A Note on the Resistance Measurement of Aluminium Wire.

An International Standard of resistance for aluminium has not yet been defined.

Whilst the recognized method of expression of resistivity is in microhms for a centimetre cube, the resistivity or conductivity of aluminium is frequently expressed for convenience in terms of standard annealed copper. The International Standard of resistance for annealed copper is expressed either as 0·15328 ohm for a metre-gramme, or as 1·7241 microhms for a centimetre cube. These two methods of expressing the standard only agree if the specific gravity is 8·89.

Whilst the volume resistivity is the most useful practical unit, in actual measurement, the mass resistivity is usually determined owing to the greater accuracy of weighing. The conversion of the one into the other is effected by assuming that the specific gravity of copper is 8·89, and though small variations in the specific gravity may occur with different samples, the universal acceptance of this procedure results in the attainment of identical values for the same sample, however and wherever the tests are made.

In the case of aluminium there is no internationally accepted value for specific gravity, and the conversion of measured values of mass resistivity into volume resistivity will give different results, according to the figure assumed for specific gravity. Any specification of aluminium resistance unless expressed in ohms for a metre-gramme should, therefore, state the value of the specific gravity to be taken for conversion.

Various types of apparatus such as the Kelvin Double Bridge and Potentiometer are available for the measurement of resistance. In making such measurements, however, certain precautions are necessary to ensure accuracy :—

(1) The arrangement of the apparatus should be such that the resistance of the contacts at the sample will not affect the values.

(2) The current connections should be such as to minimize distortion of stream lines. In general, the potential points should be taken off at positions at distances from the main current connections of not less than three times the width of the strip, or the diameter of the wire.

(3) The testing current should be small so that the temperature of the sample will not be raised so as to alter the resistance appreciably.

(4) To eliminate the effect of thermal E.M.F. two sets of readings with the current flowing in opposite directions should be taken. The mean of the two results should be taken.

(5) To ensure true determination of the temperature, either the apparatus should be so arranged that the specimen, including the current and potential contacts, is immersed in oil, or the specimens should be left for some hours in the test room previous to testing, and, during the tests, be protected from draughts.

Of the various types of apparatus, the Kelvin Double Bridge, which measures the resistance of the sample directly in terms of an invariable resistance is probably the most accurate and convenient, although when the apparatus is necessarily at a distance from the sample a potentiometer may be more suitable.

For commercial testing, the specimen is sometimes compared with a " standard copper bar " which may, or may not, be exactly in accordance with the International Standard for copper. Such a method is probably convenient and suitable for testing samples of copper having nearly the same characteristics as the " standard copper bar," but it is not satisfactory for testing a sample of which the specific gravity and temperature coefficient are appreciably different from those of the " standard copper bar." In the case of the comparison between copper and aluminium, the difference between the specific gravities of the two metals is very large, and unless a correction be applied the results of the test will be inaccurate. Moreover, a further correction is necessary owing to the difference in the temperature coefficient of the two metals. The absence of an International Standard for aluminium renders this type of apparatus unsuitable for the satisfactory comparison of copper and aluminium, as the corrections applied by one observer may differ from those used by another, and the results of the two tests will, therefore, not be comparable.

The best method of dealing with aluminium is by measurement of the actual resistance of the specimen, and by the use of appropriate corrections for specific gravity and temperature in obtaining the resistivity.

The temperature coefficient for aluminium is not greatly different from that for copper, but no value has yet been adopted as an International Standard. Hence, unless resistance measurements are made at exactly 20° C., a source of error is introduced, which may lead to discrepancies in results obtained by different experimenters at different times.

The growing importance of aluminium as an electrical conductor makes the evolution of standard values for resistivity, specific gravity and temperature coefficient very desirable, and coincidence between conductivity values obtained by different experimenters cannot be looked for until such standards are internationally adopted.

# REPORT UPON TESTS ON GALVANIZED STEEL WIRES AND CABLES FOR OVERHEAD TRANSMISSION LINES.

[Report (Ref. F/T7) received from the British Electrical and Allied Industries Research Association.]

## Contents.

Page
Introduction .. .. .. .. .. .. 1026
Scope of Investigation .. .. .. ... 1026
Material under Test .. .. .. .. 1026
Range of Samples Tested .. .. .. .. 1026
Ultimate Tensile Strength .. .. .. 1027
Extension on Fracture .. .. .. .. 1027
Limit of Proportionality .. .. .. .. 1027
Modulus of Elasticity .. .. .. .. 1027
Twist and Wrap Tests .. .. .. .. 1027
General Conclusions .. .. .. .. 1027
Results of Tests .. .. .. .. .. 1028
I. Mechanical Tests on Single Wires supplied separately .. .. .. 1028
II. Mechanical Tests on Short Stranded Cables .. .. .. .. .. 1034
III. Mechanical Tests on Long Stranded Cables .. .. .. .. .. 1037
IV. Pitch and Lay of Constituent Wires of Long Stranded Cables .. .. 1039

## Introduction.

This report deals with the results of the tests carried out at the National Physical Laboratory on galvanized steel wires and cables, both short and long lengths. The methods employed were similar to those adopted in the tests on hard drawn copper wires and cables which are described in Technical Report Ref. F/T5.*

## Scope of Investigation.

The physical properties and tests to which special attention was directed were as follows :—

Ultimate tensile strength.
Extension on fracture.
Limit of proportionality.
Modulus of elasticity.
Twist and wrap tests.

## Material under Test.

The material on which the tests, dealt with in this report, were carried out consisted of galvanized steel wires and cables as furnished for stays and supports for overhead line construction.† Single wires (see Table 1a) were obtained at the same time as the cables (see Table 1b) and purported to be of the same material. This was not borne out in one or two instances by the results obtained. For the purpose of determining the efficiency of the cables a comparison was therefore made also with tests on single wires taken from the individual cables (see Table 10).

## Range of Samples Tested.

Tests were carried out on single wires of diameters ranging from 0·064 inch to 0·160 inch, and on stranded cables of 4, 7 and 19 wires, respectively, of the above diameters.

(*a*) *Single wires supplied separately* (see Table 1a).

Tests were carried out on short lengths (10 inches). The tests on samples cut from the same coil are fairly consistent. Large variations of breaking stress are shown, however, between wires of different diameters.

Table 1a.

*Single Wires supplied separately.*

| N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Strength stated by Makers, tons per square inch |
|---|---|---|---|
| AKR | F | 0·080 | 30 |
| | | 0·128 | 30 |
| | | 0·160 | 30 |
| | | 0·080 | 40 |
| | | 0·128 | 40 |
| | | 0·160 | 40 |
| | | 0·064 | 60 |
| | | 0·080 | 60 |
| | | 0·128 | 60 |
| AKS | G | 0·080 | 30 |
| | | 0·128 | 30 |
| | | 0·160 | 30 |
| | | 0·080 | 40 |
| | | 0·128 | 40 |
| | | 0·160 | 40 |
| | | 0·064 | 60 |
| | | 0·080 | 60 |
| | | 0·128 | 60 |

There is also a wide variation between the samples of each maker, though declared to be of the same quality, viz. 30, 40 or 60 tons quality.

(*b*) *Stranded cables* (see Table 1b).

It would appear for reasons stated in Technical Report on Hard Drawn Copper Wires and Cables for Overhead Transmission Lines, Ref. F/T5, that tests on short lengths of cable are unreliable and inaccurate, except in so far as they refer to ultimate strength.

---

* See *Journal I.E.E.*, 1923, vol. 61, p. 997.

† The wires and cables referred to in this Report are not intended for use as conductors.

The results show that material different from that submitted for single-wire tests was used for the cables submitted. Several samples showed a strength as a cable greater than the sum of the strengths of the constituent wires.

In view of the discrepancies mentioned above only those cables showing consistent results in the single wire tests and short length cable tests were selected for tests on long lengths. Thus only 4 cables were tested in long lengths (100 yards), and although these gave similar results to the copper cables, viz. an increasing value of modulus on repeated loadings, the information is too slender from which to draw general conclusions.

TABLE 1B.

*Stranded Cables.*

| N.P.L. Mark | Maker | Type | Strength stated by Makers, tons per square inch |
|---|---|---|---|
| AKR4A | F | 7/·080 | 30 |
| AKR4B | F | 7/·128 | 30 |
| AKR4C | F | 4/·160 | 30 |
| AKR4D | F | 7/·160 | 30 |
| AKR4E | F | 19/·160 | 30 |
| AKR4F | F | 7/·080 | 40 |
| AKR4G | F | 7/·128 | 40 |
| AKR4H | F | 4/·160 | 40 |
| AKR4I | F | 7/·160 | 40 |
| AKR4J | F | 19/·160 | 40 |
| AKR4K | F | 7/·064 | 60 |
| AKR4L | F | 7/·080 | 60 |
| AKR4M | F | 7/·128 | 60 |
| AKS4A | G | 7/·080 | 30 |
| AKS4B | G | 7/·128 | 30 |
| AKS4C | G | 4/·160 | 30 |
| AKS4D | G | 7/·160 | 30 |
| AKS4E | G | 19/·160 | 30 |
| AKS4F | G | 7/·080 | 40 |
| AKS4G | G | 7/·128 | 40 |
| AKS4H | G | 4/·160 | 40 |
| AKS4I | G | 7/·160 | 40 |
| AKS4J | G | 19/·160 | 40 |
| AKS4K | G | 7/·064 | 60 |
| AKS4L | G | 7/·080 | 60 |
| AKS4M | G | 7/·128 | 60 |

### ULTIMATE TENSILE STRENGTH.

Large variations of ultimate tensile strength were found, and no definite values can be recommended. The results obtained by the tests are different from the declared strengths.

The variation with diameter is irregular and indefinite.

The cable strength was in some cases found to be less than, and in other cases greater than, the sum of the strengths of the individual wires. No reliable estimate of this ratio can be given.

The average efficiency of the 26 cables tested was 99 per cent, the lowest value being 94 per cent and the highest 107 per cent.

### EXTENSION ON FRACTURE.

No definite relation was observed between extension and breaking stress as in the case of copper.

If the values of ultimate stress and extension be grouped and averaged, it is found that in general the greater the extension the less is the ultimate stress.

### LIMIT OF PROPORTIONALITY.

The values of the primitive limit of proportionality are relatively unimportant, as these alter with successive loadings. Higher values may be expected with the increasing values of the modulus obtained on repeated loadings, but these are not given.

### MODULUS OF ELASTICITY.

A fair value appears to be $28 \cdot 5 \times 10^6$ lb. per square inch, as this is the figure which is approached after repeated loadings of the long cables.

A practical point arises from the fact that the true modulus of the material is higher than the value obtained on the first loading. In traction and transmission line work it has been suggested that it would be desirable if the wires and cables could have the *true value* of the modulus when *first erected.* If the repeated loadings were applied in the wire-maker's works before coiling on to drums, uncertainty would exist as to the effect of coiling and uncoiling on the final value of the modulus when the wire was strung up on site. Further elongation tests would be necessary to ascertain whether the coiling and uncoiling reduced the modulus from the *true value.**

### TWIST AND WRAP TESTS.

In general, a wire withstanding a large number of twists or wraps has a large extension, but the tests cannot be considered an indication of the quality of the wire as regards tensile strength.

It should be borne in mind, however, that twist and wrap tests can be carried out so easily that wire-makers prefer these tests to extension tests.

### GENERAL CONCLUSIONS.

The results of the tests show no close agreement such as was found in the tests on hard drawn copper.

This may be accounted for by reference to the known complexity of the structure of steel.

A complete specification of the material would call for a declaration of chemical composition and of the method of manufacture.

---

* The wire-makers on the Sub-Committee have stated that it would be impracticable to carry out the repeated loadings at the manufacturer's works.

For the purposes of overhead line construction the specification of breaking stress and extension at fracture may be sufficient, provided that the factor of safety is greater than that adopted for materials of less variable nature.

The effect of galvanizing on ultimate strength and on the behaviour under twist and wrap tests should be studied, as some part of the variations noted may be a consequence of this treatment.

## RESULTS OF TESTS.

Details of the methods of test are given in Technical Report upon Tests on Hard Drawn Copper Wires and Cables for Overhead Transmission Lines, Ref. F/T5.* The results of the tests at the N.P.L. on galvanized steel wires and cables are given on the following pages.

## I. MECHANICAL TESTS ON SINGLE WIRES SUPPLIED SEPARATELY.

The samples of single wire were supplied in the form of coils, the dimensions of which are given in Table 2.

### Determination of Breaking Load.

The load was applied slowly, the time of application being from one to three minutes, depending on the extension of the sample under test. The temperature of the air was approximately 22° C. in each case.

The results of the tensile tests, in general, on three samples of each wire are given in Table 3. All the specimens from each coil were cut from the sample end, and were not straightened before test.

Table 2.

*Dimensions of Coils of Single Wire as supplied.*

| N.P.L. Mark | Maker and Nominal Strength, tons per sq. in. | Nominal Diameter of Wire, inch | Diameter of Coil as received | |
|---|---|---|---|---|
| | | | Internal, inches | External, inches |
| AKR | F 30 | 0·080 | 21·0 | 23·0 |
| | F 30 | 0·128 | 22·5 | 25·5 |
| | F 30 | 0·160 | 28·5 | 32·0 |
| | F 40 | 0·080 | 20·5 | 23·0 |
| | F 40 | 0·128 | 23·0 | 26·5 |
| | F 40 | 0·160 | 28·5 | 32·0 |
| | F 60 | 0·064 | 16·0 | 18·0 |
| | F 60 | 0·080 | 17·0 | 19·0 |
| | F 60 | 0·128 | 29·0 | 31·5 |
| AKS | G 30 | 0·080 | 20·0 | 22·5 |
| | G 30 | 0·128 | 21·5 | 26·5 |
| | G 30 | 0·160 | 21·0 | 25·5 |
| | G 40 | 0·080 | 20·0 | 22·0 |
| | G 40 | 0·128 | 19·5 | 23·0 |
| | G 40 | 0·160 | 20·5 | 24·5 |
| | G 60 | 0·064 | 20·0 | 21·5 |
| | G 60 | 0·080 | 20·5 | 22·5 |
| | G 60 | 0·128 | 20·5 | 24·0 |

Table 3.

*Tensile Strength and Extension of Single Wires supplied separately* (see Table 1A).

| Sample | N.P.L. Mark | Maker | Diameter of Wire, inch | Cross-sectional Area of Wire, sq. in. | Yield Load, tons | Yield Stress, tons per sq. in. | Breaking Load, tons | Ultimate Stress, tons per sq. in. | Extension on | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | 10 in. | 2 in. |
| | | | | | | | | | in. | in. |
| 30 tons | AKR1A | F | 0·0815 | 0·00522 | 0·128 | 24·5 | 0·1490 | 28·5 | 1·62 | 0·41 |
| | | | | | 0·126 | 24·1 | 0·1475 | 28·2 | 1·46 | 0·36 |
| | | | | | 0·126 | 24·1 | 0·1480 | 28·3 | 1·83 | 0·50 |
| 30 tons | AKR1B | F | 0·127 | 0·01266 | 0·283 | 92·3 | 0·357 | 28·2 | 1·96 | 0·57 |
| | | | | | 0·286 | 22·6 | 0·359 | 28·4 | 1·89 | 0·51 |
| | | | | | 0·286 | 22·6 | 0·3575 | 28·3 | 1·80 | 0·47 |
| 30 tons | AKR1C | F | 0·162 | 0·02061 | 0·607 | 29·5 | 0·738 | 35·8 | 0·99 | 0·34 |
| | | | | | 0·636 | 30·9 | 0·726 | 35·3 | 0·88 | 0·33 |
| | | | | | 0·635 | 30·8 | 0·7385 | 35·8 | 1·04 | 0·31 |
| 40 tons | AKR1D | F | 0·080 | 0.00503 | 0·2515 | 50·0 | 0·2515 | 50·0 | 0·07 | 0·06 |
| | | | | | 0·2510 | 49·8 | 0·2510 | 49·8 | 0·06 | 0·05 |
| | | | | | 0·2450 | 48·7 | 0·2450 | 48·7 | 0·08 | 0·06 |
| 40 tons | AKR1E | F | 0·1285 | 0·01296 | 0·587 | 45·3 | 0·614 | 47·4 | 0·77 | 0·22 |
| | | | | | 0·576 | 44·5 | 0·616 | 47·6 | 0·82 | 0·22 |
| | | | | | 0·573 | 44·3 | 0·601 | 46·4 | 0·76 | 0·24 |
| 40 tons | AKR1F | F | 0·160 | 0·0201 | 1·036 | 51·5 | 1·093 | 54·4 | 0·54 | 0·18 |
| | | | | | 1·043 | 51·9 | 1·092 | 54·3 | 0·57 | 0·16 |
| | | | | | 1·0415 | 51·8 | 1·094 | 54·4 | 0·57 | 0·18 |

---

* The original Report was accompanied by drawings showing the apparatus used. These can be inspected at the E.R.A. office.

TABLE 3—*Continued.*

*Tensile Strength and Extension of Single Wires supplied separately—continued.*

| Sample | N.P.L. Mark | Maker | Diameter of Wire, inch | Cross-sectional Area of Wire, sq. in. | Yield Load, ton | Yield Stress, tons per sq. in. | Breaking Load, ton | Ultimate Stress, tons per sq. in. | Extension on 10 in. | Extension on 2 in. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | in. | in. |
| 60 tons | AKR1G | F | 0·064 | 0·00322 | 0·187 | 58·1 | 0·219 | 68·0 | 0·47 | 0·13 |
| | | | | | 0·190 | 59·0 | 0·220 | 68·3 | 0·45 | 0·13 |
| | | | | | 0·190 | 59·0 | 0·220 | 68·3 | 0·44 | 0·11 |
| 60 tons | AKR1H | F | 0·0815 | 0·00522 | 0·313 | 60·0 | 0·366 | 70·1 | 0·48 | 0·13 |
| | | | | | 0·313 | 60·0 | 0·364 | 69·8 | 0·49 | 0·14 |
| | | | | | 0·315 | 60·3 | 0·364 | 69·8 | 0·47 | 0·14 |
| 60 tons | AKR1I | F | 0·129 | 0·01307 | 0·670 | 51·3 | 0·738 | 56·5 | 0·51 | 0·17 |
| | | | | | 0·680 | 52·0 | 0·727 | 55·6 | 0·46 | 0·16 |
| | | | | | 0·671 | 51·3 | 0·740 | 56·6 | 0·52 | 0·15 |
| 30 tons | AKS1A | G | 0·081 | 0·00515 | 0·176 | 34·2 | 0·285 | 55·3 | 1·02 | 0·26 |
| | | | | | 0·171 | 33·2 | 0·288 | 55·9 | 1·09 | 0·29 |
| | | | | | 0·1755 | 34·1 | 0·286 | 55·5 | 1·00 | 0·28 |
| | | | | | 0·177 | 34·3 | 0·288 | 55·9 | 1·07 | 0·29 |
| 30 tons | AKS1B | G | 0·129 | 0·01307 | 0·268 | 20·5 | 0·369 | 28·2 | 1·06 | 0·30 |
| | | | | | 0·269 | 20·6 | 0·361 | 27·6 | 1·25 | 0·35 |
| | | | | | 0·264 | 20·2 | 0·363 | 27·8 | 1·11 | 0·31 |
| | | | | | 0·275 | 21·0 | 0·3645 | 27·9 | 1·18 | 0·37 |
| 30 tons | AKS1C | G | 0·160 | 0·0201 | 0·767 | 38·2 | 0·8145 | 40·5 | 0·62 | 0·20 |
| | | | | | 0·741 | 36·9 | 0·789 | 39·3 | 0·50 | 0·19 |
| | | | | | 0·723 | 36·0 | 0·796 | 39·6 | 0·50 | 0·20 |
| | | | | | 0·748 | 37·2 | 0·8125 | 40·4 | — | — |
| 40 tons | AKS1D | G | 0·080 | 0·00503 | 0·204 | 40·5 | 0·2735 | 54·3 | 0·03 | 0·03 |
| | | | | | 0·235 | 46·7 | 0·2680 | 53·2 | 0·03 | 0·03 |
| | | | | | 0·240 | 47·7 | 0·2580 | 51·2 | 0·04 | 0·04 |
| | | | | | 0·238 | 47·3 | 0·2590 | 51·5 | 0·06 | 0·06 |
| 40 tons | AKS1E | G | 0·1285 | 0·01297 | 0·405 | 31·3 | 0·6445 | 49·8 | — | — |
| | | | | | 0·463 | 35·8 | 0·5985 | 46·2 | 0·34 | 0·18 |
| | | | | | 0·450 | 34·8 | 0·6045 | 46·7 | 0·40 | 0·19 |
| | | | | | 0·620 | 47·8 | 0·7000 | 54·0 | — | — |
| | | | | | 0·538 | 41·6 | 0·6980 | 53·9 | 0·34 | 0·15 |
| | | | | | 0·599 | 46·3 | 0·6860 | 53·0 | 0·40 | 0·14 |
| 40 tons | AKS1F | G | 0·163 | 0·02087 | 0·860 | 41·2 | 0·9415 | 45·2 | 0·37 | 0·16 |
| | | | | | 0·875 | 42·0 | 0·9770 | 46·8 | — | — |
| | | | | | 0·896 | 43·0 | 0·9840 | 47·2 | 0·53 | 0·17 |
| | | | | | 0·790 | 37·9 | 0·9210 | 44·2 | 0·54 | 0·21 |
| | | | | | 0·839 | 40·2 | 0·9150 | 43·8 | 0·46 | 0·21 |
| | | | | | 0·830 | 39·8 | 0·9220 | 44·2 | — | — |
| 60 tons | AKS1G | G | 0·0645 | 0·00327 | 0·177 | 54·2 | 0·2015 | 61·6 | 0·54 | 0·14 |
| | | | | | 0·170 | 52·0 | 0·2015 | 61·6 | 0·43 | 0·12 |
| | | | | | 0·172 | 52·6 | 0·2015 | 61·6 | 0·47 | 0·13 |
| | | | | | 0·1735 | 53·0 | 0·2015 | 61·6 | 0·46 | 0·15 |
| 60 tons | AKS1H | G | 0·082 | 0·00528 | 0·365 | 69·1 | 0·3995 | 75·6 | 0·44 | 0·12 |
| | | | | | 0·348 | 65·9 | 0·3985 | 75·4 | 0·50 | 0·14 |
| | | | | | 0·358 | 67·8 | 0·3990 | 75·5 | 0·50 | 0·15 |
| | | | | | 0·357 | 67·5 | 0·3970 | 75·2 | 0·47 | 0·14 |
| 60 tons | AKS1I | G | 0·126 | 0·01247 | 0·616 | 49·4 | 0·7770 | 62·3 | 0·67 | 0·20 |
| | | | | | 0·621 | 49·8 | 0·7745 | 62·1 | 0·62 | 0·20 |
| | | | | | 0·605 | 48·5 | 0·7740 | 62·1 | 0·68 | 0·20 |
| | | | | | 0·621 | 49·8 | 0·7765 | 62·3 | 0·66 | 0·18 |

TABLE 4.

*Limits of Proportionality, Modulus and Extension of Single Wires supplied separately* (see Table 1A).

| Sample | 30 Tons | | | 40 Tons | | | 60 Tons | | |
|---|---|---|---|---|---|---|---|---|---|
| **N.P.L. mark, AKR**<br>**Maker, F.** | | | | | | | | | |
| Diameter of wire, inch | 0·0805 | 0·1274 | 0·1616 | 0·0806 | 0·130 | 0·1603 | 0·0636 | 0·0805 | 0·1287 |
| Cross-sectional area of wire, square inch | 0·00509 | 0·01274 | 0·0205 | 0·00510 | 0·01327 | 0·02018 | 0·00318 | 0·00509 | 0·01301 |
| Primitive limit of proportionality, ton | 0·0425 | 0·086 | 0·34 | 0·065 | 0·140 | 0·260 | 0·096 | 0·090 | 0·170 |
| Primitive limit of proportionality, tons per square inch | 8·4 | 6·8 | 16·6 | 12·7 | 10·6 | 12·9 | 30·2 | 17·7 | 13·1 |
| Yield load, ton | 0·120 | 0·271 | 0·622 | 0·224 | 0·530 | 0·958 | 0·178 | 0·305 | 0·628 |
| Yield stress, tons per square inch | 23·6 | 21·3 | 30·3 | 43·9 | 40·0 | 47·5 | 56·0 | 60·0 | 48·3 |
| Breaking load, tons | 0·1495 | 0·350 | 0·814 | 0·2465 | 0·592 | 1·0175 | 0·2185 | 0·363 | 0·710 |
| Ultimate stress, tons per square inch | 29·4 | 27·5 | 39·7 | 48·3 | 44·7 | 50·5 | 68·7 | 71·3 | 54·6 |
| Modulus (1st), lb. per square inch × $10^{-6}$ | 26·3 | 27·0 | 28·0 | 28·2 | 27·7 | 27·9 | 27·4 | 28·9 | 28·8 |
| Modulus (2nd), lb. per square inch × $10^{-6}$ | 27·2 | 27·5 | 28·3 | 28·7 | 28·3 | 28·2 | 28·3 | 29·3 | 28·9 |
| Extension on 10 inches, inches | 1·41 | 1·96 | 0·88 | 0·13 | 0·75 | 0·45 | 0·43 | 0·48 | 0·41 |
| Extension on 2 inches, inch | 0·40 | 0·49 | 0·30 | 0·12 | 0·23 | 0·17 | 0·13 | 0·14 | 0·13 |
| **N.P.L. mark, AKS.**<br>**Maker, G.** | | | | | | | | | |
| Diameter of wire, inch | 0·0813 | 0·1287 | 0·1594 | 0·0803 | 0·129 | 0·1632 | 0·0646 | 0·0822 | 0·1257 |
| Cross-sectional area of wire, square inch | 0·00519 | 0·01301 | 0·01995 | 0·00506 | 0·01307 | 0·02092 | 0·00328 | 0·00531 | 0·01241 |
| Primitive limit of proportionality, ton | 0·09 | 0·136 | 0·222 | 0·0835 | 0·136 | 0·180 | 0·079 | 0·134 | 0·252 |
| Primitive limit of proportionality, tons per square inch | 17·3 | 10·4 | 11·1 | 16·5 | 10·4 | 8·6 | 24·1 | 25·2 | 20·3 |
| Yield load, ton | 0·173 | 0·256 | 0·740 | 0·229 | 0·551 | 0·789 | 0·165 | 0·355 | 0·620 |
| Yield stress, tons per square inch | 33·3 | 19·7 | 37·1 | 45·3 | 42·2 | 37·7 | 50·3 | 66·9 | 50·0 |
| Breaking load, ton | 0·287 | 0·366 | 0·7955 | 0·243 | 0·5775 | 0·9595 | 0·201 | 0·3945 | 0·770 |
| Ultimate stress, tons per square inch | 55·3 | 28·1 | 39·9 | 48·0 | 44·2 | 45·9 | 61·3 | 74·3 | 62·2 |
| Modulus (1st), lb. per square inch × $10^{-6}$ | 27·2 | 27·7 | 28·2 | 27·7 | 27·6 | 27·8 | 27·8 | 28·4 | 28·5 |
| Modulus (2nd), lb. per square inch × $10^{-6}$ | 28·4 | 28·1 | 28·2 | 28·7 | 28·7 | 28·1 | 28·5 | 29·2 | 29·1 |
| Extension on 10 inches, inches | 1·05 | 1·06 | 0·47 | 0·15 | 0·41 | 0·45 | 0·54 | 0·48 | 0·67 |
| Extension on 2 inches, inch | 0·28 | 0·35 | 0·18 | 0·13 | 0·18 | 0·17 | 0·15 | 0·13 | 0·19 |

The diameters of the wires recorded were the exterior values and include the thickness of the zinc coating.

### TABLE 5.

*Twist Tests on Single Wires supplied separately* (see Table 1A).

| Sample, tons | N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Number of Twists on | |
|---|---|---|---|---|---|
| | | | | 6-in. Length | 3-in. Length |
| 30 | AKR2A | F | 0·080 | 44<br>44<br>46 | 26<br>23<br>18 |
| 30 | AKR2B | F | 0·128 | 33<br>31<br>33 | —<br>—<br>— |
| 30 | AKR2C | F | 0·160 | 25<br>27<br>24½ | —<br>—<br>— |
| 40 | AKR2D | F | 0·080 | 20<br>17<br>19 | 11<br>9½<br>10 |
| 40 | AKR2E | F | 0·128 | 5½<br>6<br>4½ | —<br>—<br>— |
| 40 | AKR2F | F | 0·160 | 7<br>10<br>8 | —<br>—<br>— |
| 60 | AKR2G | F | 0·064 | 12<br>7½<br>11 | 12<br>7<br>8 |
| 60 | AKR2H | F | 0·080 | 7<br>6½<br>7½ | 5<br>5<br>4 |
| 60 | AKR2I | F | 0·128 | 4<br>4½<br>5 | —<br>—<br>— |
| 30 | AKS2A | G | 0·080 | 30<br>27<br>30 | 16<br>16<br>17 |
| 30 | AKS2B | G | 0·128 | 16½<br>16<br>16 | —<br>—<br>— |
| 30 | AKS2C | G | 0·160 | 4½<br>5<br>6 | —<br>—<br>— |
| 40 | AKS2D | G | 0·080 | 32<br>21<br>18 | 14<br>10½<br>17 |
| 40 | AKS2E | G | 0·128 | 3<br>3<br>4½ | —<br>—<br>— |
| 40 | AKS2F | G | 0·160 | 5<br>4½<br>5 | —<br>—<br>— |
| 60 | AKS2G | G | 0·064 | 8<br>9<br>7½ | 4½<br>5<br>5 |
| 60 | AKS2H | G | 0·080 | 14½<br>20<br>15 | 13<br>9<br>9 |
| 60 | AKS2I | G | 0·128 | 9<br>11<br>9 | —<br>—<br>— |

### TABLE 6.

*Wrap Tests on Single Wires supplied separately* (see Table 1A).

| Sample, tons | N.P.L. Mark | Maker | Nominal Diameter of Wire, inch | Statement of Results |
|---|---|---|---|---|
| 30 | AKR3A | F | 0·080 | 9, 6, 6, 6, 6, 2<br>9, 6, 6, 6, 6, 2<br>9, 6, 6, 6, 6, 1 |
| 30 | AKR3B | F | 0·128 | 9, 6, 6, 6, 6, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 6, 6, 3<br>9, 6, 6, 6, 6, 6, 6, 6, 6, 3 |
| 30 | AKR3C | F | 0·160 | 9, 6, 6, 6, 6, 6, 6, 2<br>9, 6, 6, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 6, 6, 2 |
| 40 | AKR3D | F | 0·080 | 9, 6, 6, 3<br>9, 6, 6, 6, 2<br>9, 6, 6, 5 |
| 40 | AKR3E | F | 0·128 | 9, 6, 1<br>9, 1<br>9, 1 |
| 40 | AKR3F | F | 0·160 | 9, 6, 6, 6, 6, 6, 6, 2<br>9, 6, 6, 6, 6, 6, 6, 2<br>9, 6, 6, 6, 6, 6, 6, 2 |
| 60 | AKR3G | F | 0·064 | 9, 6, 6, 6, 6, 5<br>9, 6, 6, 6, 6, 2<br>9, 6, 6, 6, 6, 3 |
| 60 | AKR3H | F | 0·080 | 9, 6, 6, 5<br>9, 6, 6, 1<br>9, 6, 6, 2 |
| 60 | AKR3I | F | 0·128 | 9, 3<br>9, 5<br>9, 6 |
| 30 | AKS3A | G | 0·080 | 9, 6, 6, 6, 6, 6, 6, 3<br>9, 6, 6, 6, 6, 6, 6, 5<br>9, 6, 6, 6, 6, 4 |
| 30 | AKS3B | G | 0·128 | 9, 6, 6, 4<br>9, 6, 6, 6, 5<br>9, 6, 6, 2 |
| 30 | AKS3C | G | 0·160 | 9, 6, 6, 6, 6, 2<br>9, 6, 6, 6, 6, 3<br>9, 6, 6, 6, 6, 1 |
| 40 | AKS3D | G | 0·080 | 9, 6, 6, 6, 6, 1<br>9, 6, 6, 3<br>9, 6, 6, 6, 6, 1 |
| 40 | AKS3E | G | 0·128 | 9, 6, 6, 1<br>9, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 2 |
| 40 | AKS3F | G | 0·160 | 9, 6, 6, 4<br>9, 6, 6, 3<br>9, 6, 6, 2 |
| 60 | AKS3G | G | 0·064 | 9, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 1<br>9, 6, 6, 6, 6, 2 |
| 60 | AKS3H | G | 0·080 | 9, 6, 1<br>9, 6, 6, 2<br>9, 6, 6, 3 |
| 60 | AKS3I | G | 0·128 | 9, 6, 1<br>9, 6, 2<br>9, 6, 1 |

More than three tests were carried out on each sample of galvanized steel wire by maker G in view of the marked differences that were noted in the breaking loads of specimens from both the samples of wire AKS1E and AKS1F, especially the former. The additional values were obtained as a check on the previous set of values. No change in the diameter, or the presence of kinks or other damage, was observed between the specimens in each set, and each piece was cut from the same end of the coil.

TABLE 7.

*Summary of Results of Tests on Single Wires supplied separately* (see Table 1A).

| Sample | Nominal Diameter of Wire, inch | Primitive Limit of Proportionality, tons per sq. in. | Ultimate Stress, Average Values from Tables 3 and 4, tons per sq. in. | Extension, Average Values from Tables 3 and 4, on | | Modulus of Elasticity, lb. per sq. in. $\times 10^{-6}$ | | Average Twists on | | Minimum Value for Wrap Test |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 10 inches, in. | 2 inches, in. | 1st | 2nd | 6 inches | 3 inches | |
| N.P.L. Mark, AKR.<br>Maker, F. | | | | | | | | | | |
| 30 tons | 0·080 | 8·4 | 28·6 | 1·58 | 0·42 | 26·3 | 27·2 | 45 | 22 | 9, 6, 6, 6, 6 |
| | 0·128 | 6·8 | 28·1 | 1·90 | 0·51 | 27·0 | 27·5 | 32 | — | 9, 6, 6, 6, 6, 6, 6 |
| | 0·160 | 16·6 | 36·6 | 0·95 | 0·32 | 28·0 | 28·3 | 26 | — | 9, 6, 6, 6, 6, 6, 6 |
| 40 tons | 0·080 | 12·7 | 49·2 | 0·09 | 0·07 | 28·2 | 28·7 | 19 | 10 | 9, 6, 6 |
| | 0·128 | 10·6 | 46·5 | 0·78 | 0·23 | 27·7 | 28·3 | 5½ | — | 9, 1 |
| | 0·160 | 12·9 | 53·4 | 0·53 | 0·17 | 27·9 | 28·2 | 8½ | — | 9, 6, 6, 6, 6, 6, 6 |
| 60 tons | 0·064 | 38·2 | 68·3 | 0·45 | 0·13 | 27·4 | 28·3 | 10 | 9 | 9, 6, 6, 6, 6 |
| | 0·080 | 17·7 | 71·2 | 0·48 | 0·14 | 28·9 | 29·3 | 7 | 5 | 9, 6, 6 |
| | 0·128 | 13·1 | 55·8 | 0·48 | 0·15 | 28·8 | 28·9 | 4½ | — | 9, 1 |
| N.P.L. Mark, AKS.<br>Maker, G. | | | | | | | | | | |
| 30 tons | 0·080 | 17·3 | 55·6 | 1·05 | 0·28 | 27·2 | 28·4 | 29 | 17 | 9, 6, 6, 6, 6 |
| | 0·128 | 10·4 | 27·9 | 1·13 | 0·34 | 27·7 | 28·1 | 16 | — | 9, 6, 6 |
| | 0·160 | 11·1 | 40·0 | 0·52 | 0·19 | 28·2 | 28·2 | 5 | — | 9, 6, 6, 6, 6 |
| 40 tons | 0·080 | 16·5 | 51·6 | 0·06 | 0·06 | 27·7 | 28·7 | 24 | 14 | 9, 6, 6 |
| | 0·128 | 10·4 | 49·7 | 0·38 | 0·17 | 27·6 | 28·7 | 3½ | — | 9, 6, 6 |
| | 0·160 | 8·6 | 49·3 | 0·47 | 0·18 | 27·8 | 28·1 | 5 | — | 9, 6, 6 |
| 60 tons | 0·064 | 24·1 | 61·6 | 0·49 | 0·14 | 27·8 | 28·5 | 8 | 5 | 9, 6, 6, 6, 6 |
| | 0·080 | 25·2 | 75·2 | 0·48 | 0·14 | 28·4 | 29·2 | 17 | 10½ | 9, 6 |
| | 0·128 | 20·3 | 62·2 | 0·66 | 0·20 | 28·5 | 29·1 | 10 | — | 9, 6 |

## DETERMINATION OF THE LIMIT OF PROPORTIONALITY, MODULUS, AND EXTENSION.

Tensile tests were carried out on straightened lengths of wire having 10 inches between the grips. The extension on a 2-inch middle portion of the wire was measured by means of a Marten's mirror extensometer. The primitive limit of proportionality and the modulus at first loading were obtained by loading up in steps to a point just beyond the limit of proportionality. The load was then removed, and a second modulus obtained by again loading up to the same point.

The results are given in Table 4.

All the wires were straightened previously to testing. Results of typical tests are shown in Figs. 1 and 2. The value of the limit of proportionality has been taken as that load at which the first deviation from Hooke's Law was observed upon the first loading of the wire.

The value of the primitive limit of proportionality is not of very great importance. If the wire is reloaded after the limit of proportionality has been exceeded a new and higher value of the limit is obtained, the amount of the increase depending upon the amount by which the primitive limit of proportionality has been exceeded.

## TWIST TESTS.

The twist tests were carried out in accordance with the British Engineering Standards Association Specification for Hard Drawn Copper Wire. The specimen

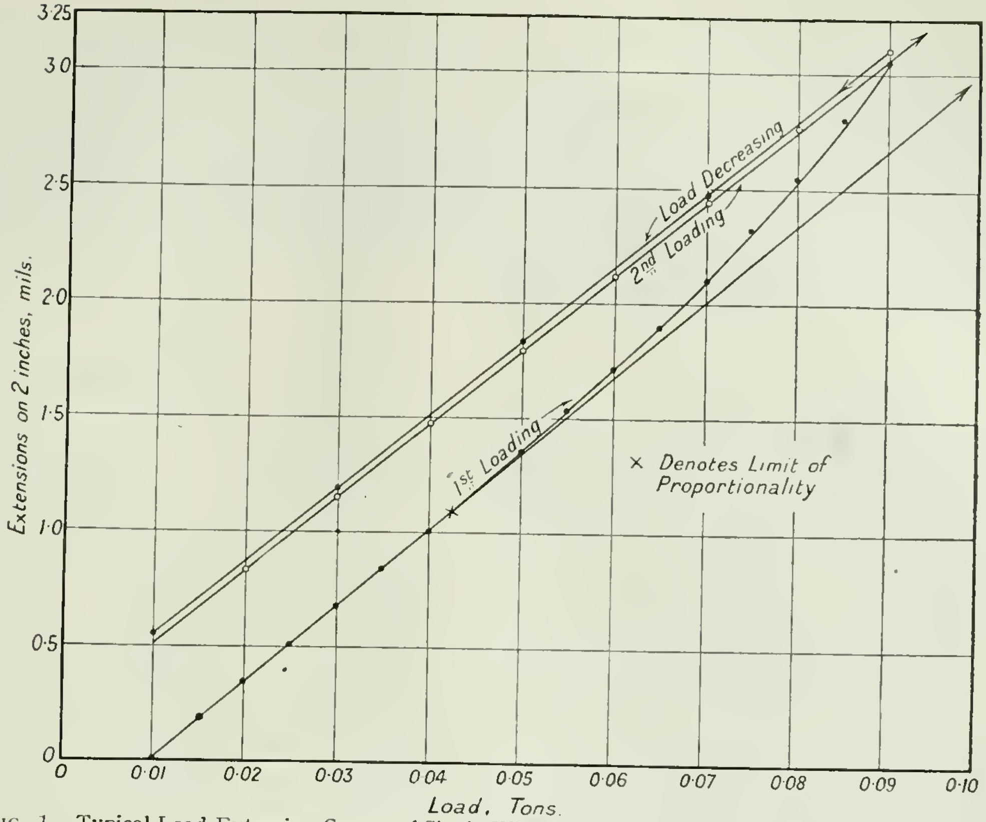


FIG. 1.—Typical Load-Extension Curves of Single Wires supplied separately by Maker F (30 tons)

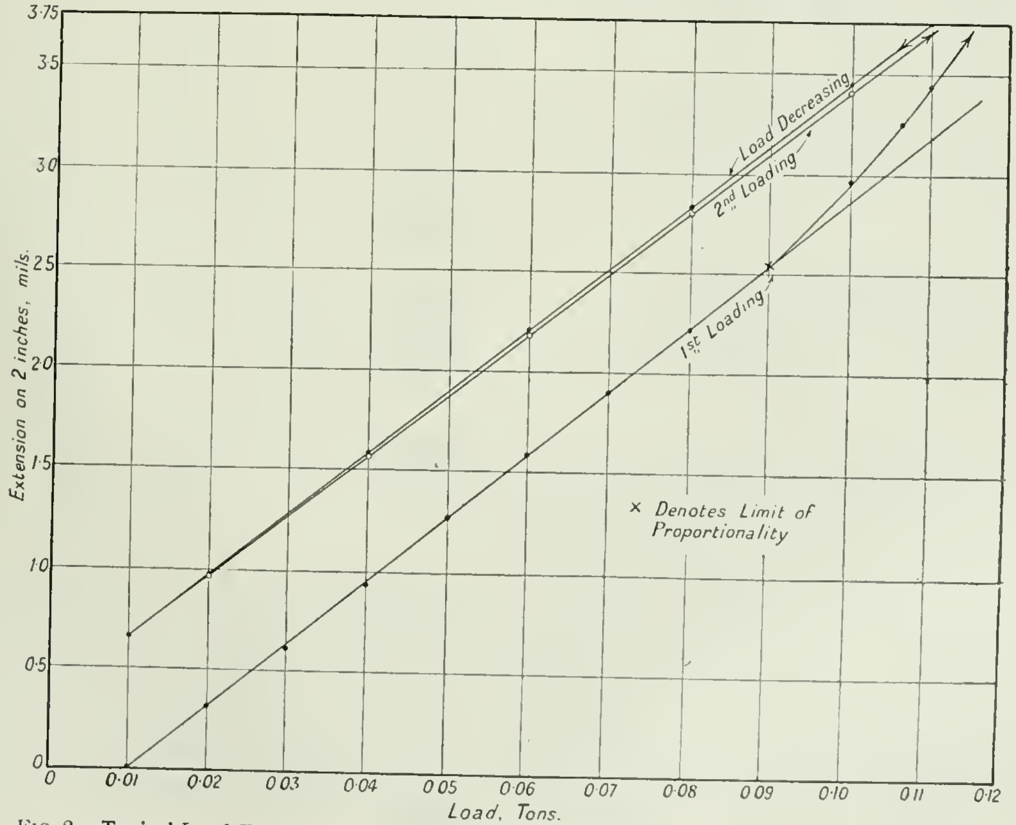


FIG. 2.—Typical Load-Extension Curves of Single Wires supplied separately by Maker G (30 tons).

was gripped in two jaws one fixed in the fast headstock of a small lathe, and the other fixed in a loose headstock, but allowed to move axially. The lathe was made to rotate at 40 revolutions per minute until fracture occurred, and the number of twists was indicated by the spiral formed by a mark previously painted along the wire. All the wires were straightened before test and were cut from the same end of the coil as the tensile test specimens. The distance between the jaws was set at 6 inches for all the samples, but additional tests on 3-inch lengths were carried out on the small diameter wires. The results of these tests are given in Table 5.

### WRAP TESTS.

The British Engineering Standards Association Specification for Hard Drawn Copper Wire states that " the test sample shall be closely lapped round wire of its own diameter, unlapped, and again closely lapped round wire of its own diameter in the same direction as the first lapping without breaking."

Tests were carried out on these lines, but the wrapping and unwrapping was continued until fracture occurred. It was found necessary to wrap on 9 or 12 turns in the first wrapping, and then wrap and unwrap 6 turns as required in the test, so as to make the unwrapping operation easier during the last few turns.

The results of these tests are given in Table 6. In this table the results are stated in the following form : the first, third, fifth, etc., numbers represent the wrapping operation, the intermediate numbers the unwrapping operation.

### SUMMARY OF RESULTS.

The results given in the previous tables have been summarized in Table 7, average values being given in place of the full detail results.

## II. MECHANICAL TESTS ON SHORT STRANDED CABLES.

Details of the stranded cables on which the tests were carried out are given in Table 8.

### DETERMINATION OF BREAKING LOAD.

*Strength of the constituent wires of the cables.*—To determine the efficiencies of the various cables, it was originally intended to compare the cable breaking stress with the results of single wire tests. A few preliminary tests showed that great differences existed between the actual and stated strengths of the wire used in the cables. The labels on three cables had become mixed, and the actual strength of a fourth cable bore no relation to the stated strength. It was also found that up to as much as 25 per cent difference in strength existed between wires of the same cable. It was decided, therefore, to determine the breaking load of the wires by testing to destruction each wire of which the cable was composed. Thus, 218 wire tests have been carried out, in addition to the 53 samples of cable tested to destruction.* The wire tests were carried out on the 2-ton single-lever machine.

*Selection of samples.*—A length of 9 feet was cut off from each cable. One length of 4 feet was cut off each end of this length, one such length being used for the determination of the breaking load and the other for the determination of the limit of proportionality, modulus, etc. The central portion was unstranded, and each wire tested to destruction.

TABLE 8.

*Stranded Cables.*

| N.P.L. Mark | Maker | Type | Strength stated by Maker, tons per sq. in. | Diameter of Cable, inch |
|---|---|---|---|---|
| AKR4A | F | 7/·080 | 30 | 0·25 |
| AKR4B | F | 7/·128 | 30 | 0·38 |
| AKR4C | F | 4/·160 | 30 | 0·38 |
| AKR4D | F | 7/·160 | 30 | 0·47 |
| AKR4E | F | 19/·160 | 30 | 0·78 |
| AKR4F | F | 7/·080 | 40 | 0·25 |
| AKR4G | F | 7/·128 | 40 | 0·38 |
| AKR4H | F | 4/·160 | 40 | 0·38 |
| AKR4I | F | 7/·160 | 40 | 0·47 |
| AKR4J | F | 19/·160 | 40 | 0·78 |
| AKR4K | F | 7/·064 | 60 | 0·19 |
| AKR4L | F | 7/·080 | 60 | 0·25 |
| AKR4M | F | 7/·128 | 60 | 0·38 |
| AKS4A | G | 7/·080 | 30 | 0·25 |
| AKS4B | G | 7/·128 | 30 | 0·38 |
| AKS4C | G | 4/·160 | 30 | 0·38 |
| AKS4D | G | 7/·160 | 30 | 0·47 |
| AKS4E | G | 19/·160 | 30 | 0·78 |
| AKS4F | G | 7/·080 | 40 | 0·25 |
| AKS4G | G | 7/·128 | 40 | 0·38 |
| AKS4H | G | 4/·160 | 40 | 0·38 |
| AKS4I | G | 7/·160 | 40 | 0·47 |
| AKS4J | G | 19/·160 | 40 | 0·78 |
| AKS4K | G | 7/·064 | 60 | 0·19 |
| AKS4L | G | 7/·080 | 60 | 0·25 |
| AKS4M | G | 7/·128 | 60 | 0·38 |

*Elongation at fracture.*—Gauge marks, 8 inches apart, were made on the cable at the commencement of the tests. In many cases the cable unstranded in the vicinity of the fracture, and it was found impossible to measure the elongation. In the majority of cases corresponding ends of broken wires were misplaced, and it was extremely difficult to place the fractured ends in their true relative positions. The measured elongations are, therefore, given chiefly for their relative values. The accuracy of their values cannot be relied upon.

---

* Out of the 53 cables tested to destruction only one broke in the grips.

*Conditions of tests.*—The length of cable between the grips was 14 inches. The results of tests to fracture on the cables and constituent wires are given in Table 9.

It will be noted from the results that the strengths do not agree with those stated by the makers in the case of four cables all manufactured by maker G.

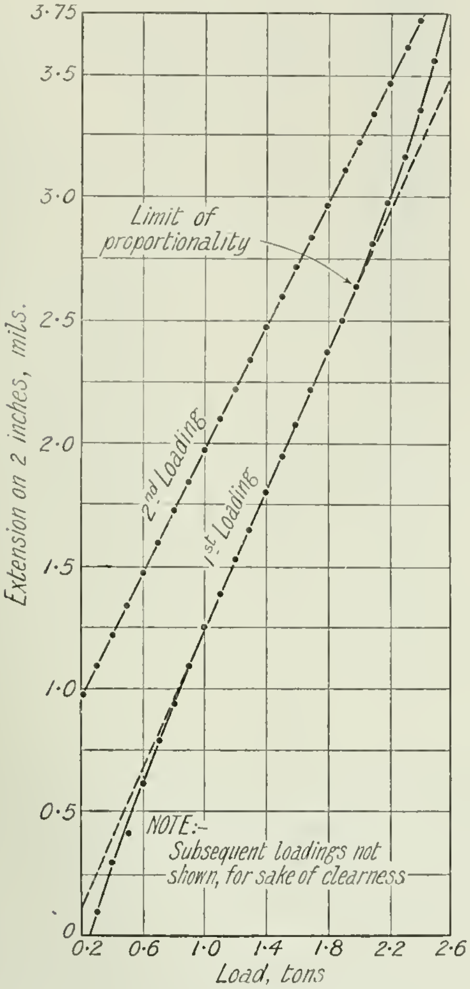


FIG. 3.—Typical Load-Extension Curves of Medium Short Stranded Cables (7/·160).

The four cables are as follows :—

| N.P.L. Mark | Type | Stated Strength of Wire of which Cable is composed, tons per sq. in. |
|---|---|---|
| AKS4B | 7/·128 | 30 |
| AKS4E | 19/·160 | 30 |
| AKS4J | 19/·160 | 40 |
| AKS4M | 7/·128 | 60 |

The results indicate that the maker's labels on AKS4B and AKS4M have been mixed. This is also, probably, the case with the other pair of cables, i.e. AKS4E and AKS4J, though the results do not indicate this so clearly, but rather indicate different material.

In the case of three cables, made by maker F, whose N.P.L. marks are AKR4H, AKR4I, AKR4J, the difference in ultimate strengths of the cables and of the single wires indicates that different material has been used for the cables to that submitted for the tests on the single wires.

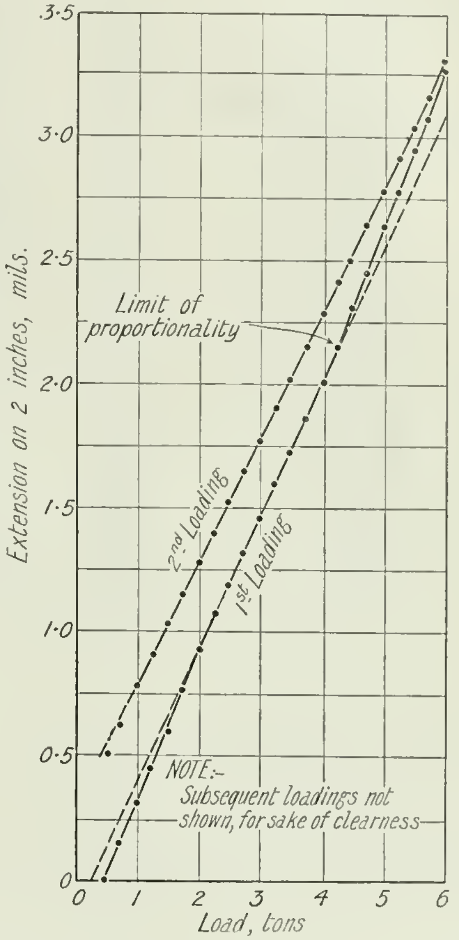


FIG. 4.—Typical Load-Extension Curves of Large Short Stranded Cables (19/·160).

Table 10, showing the efficiencies of the cables as compared with the constituent wires and single wire tests, will make this point clear.

Column 1 gives particulars of the cables and their ultimate stresses.

Column 2 gives the ultimate stress of the constituent wires.

Column 3 is a summary of the single wire tests.

Column 4 gives the percentage strength of the cable as compared with that of the constituent wires, so that

TABLE 9.

*Tensile Strength of Short Cables and of Constituent Wires.*

| Sample | N.P.L. Mark | Maker | Type | Short Cables | | | | Constituent Wires | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Cross-sectional Area, sq. in. | Breaking Load, tons | Ultimate Stress, tons per sq. in. | Per cent Extension on 8 in. | Total Breaking Load, tons | Ultimate Stress, tons per sq. in. |
| 30 tons | AKR4A | F | 7/·080 | 0·0365 | 1·16 | 31·8 | 5 | 1·09 | 29·9 |
| | AKR4B | F | 7/·128 | 0·0889 | 2·60 | 29·2 | 20 | 2·65 | 29·8 |
| | AKR4C | F | 4/·160 | 0·0792 | 2·63 | 33·2 | 13 | 2·56 | 32·3 |
| | AKR4D | F | 7/·160 | 0·1385 | 4·6 | 33·2 | 11 | 4·66 | 33·6 |
| | AKR4E | F | 19/·160 | 0·3793 | 12·7 | 33·5 | 14 | 13·1 | 34·5 |
| 40 tons | AKR4F | F | 7/·080 | 0·0361 | 1·63 | 45·2 | 8 | 1·74 | 48·2 |
| | AKR4G | F | 7/·128 | 0·0905 | 3·95 | 43·6 | 9 | 3·9 | 43·1 |
| | AKR4H | F | 4/·160 | 0·0814 | 3·13 | 38·4 | 13 | 3·22 | 39·6 |
| | AKR4I | F | 7/·160 | 0·1443 | 5·51 | 38·2 | 12 | 5·62 | 38·9 |
| | AKR4J | F | 19/·160 | 0·3925 | 14·9 | 38·0 | — | 15·5 | 39·5 |
| 60 tons | AKR4K | F | 7/·064 | 0·0224 | 1·57 | 70·1 | — | 1·57 | 70·1 |
| | AKR4L | F | 7/·080 | 0·0352 | 2·60 | 73·9 | 7 | 2·54 | 72·2 |
| | AKR4M | F | 7/·128 | 0·0911 | 6·23 | 68·4 | 4 | 6·30 | 69·2 |
| 30 tons | AKS4A | G | 7/·080 | 0·0355 | 1·86 | 52·4 | 11 | 1·88 | 52·9 |
| | AKS4B | G | 7/·128 | 0·0879 | 5·74 | 65·3 | 10 | 5·84 | 66·4 |
| | AKS4C | G | 4/·160 | 0·0800 | 3·05 | 38·1 | 8 | 2·86 | 35·7 |
| | AKS4D | G | 7/·160 | 0·1363 | 5·0 | 36·7 | 8 | 5·06 | 37·1 |
| | AKS4E | G | 19/·160 | 0·3818 | 16·6 | 43·5 | 11 | 17·12 | 44·8 |
| 40 tons | AKS4F | G | 7/·080 | 0·0358 | 1·82 | 50·8 | 4 | 1·90 | 53·1 |
| | AKS4G | G | 7/·128 | 0·0903 | 4·28 | 47·4 | 4 | 4·35 | 48·2 |
| | AKS4H | G | 4/·160 | 0·0813 | 3·54 | 43·5 | 7 | 3·58 | 44·0 |
| | AKS4I | G | 7/·160 | 0·1410 | 5·75 | 40·8 | 7 | 5·80 | 41·1 |
| | AKS4J | G | 19/·160 | 0·3722 | 13·86 | 37·2 | 11 | 14·3 | 38·4 |
| 60 tons | AKS4K | G | 7/·064 | 0·0226 | 1·54 | 68·1 | 4 | 1·47 | 65·0 |
| | AKS4L | G | 7/·080 | 0·0374 | 2·78 | 74·3 | 3 | 2·84 | 75·9 |
| | AKS4M | G | 7/·128 | 0·0909 | 2·70 | 29·7 | — | 2·68 | 29·5 |

Efficiency on constituent wires, per cent

$$= \frac{\text{Ultimate strength of cable (tons per sq. in.)}}{\text{Total ultimate strength of constituent wires (tons per sq: in.)}} \times 100$$

Column 5 gives the percentage strength of the cable as compared with the results obtained on the single wire tests.

Efficiency on single wire, per cent

$$= \frac{\text{Ultimate strength of cable (tons per sq. in.)}}{\text{Ultimate strength of single wire (tons per sq. in.)}} \times 100$$

## DETERMINATION OF LIMIT OF PROPORTIONALITY AND MODULUS.

The length of cable under test between the edges of the grips was 14 inches. A Ewing extensometer was used to measure the strains which were observed on a length of 8 inches. The primitive limit of proportionality and the modulus at first loading were obtained by loading up in equal steps to a point just beyond the load where the limit of proportionality was observed. The load was then removed, and a second modulus obtained by loading up again to the same point.

It will be noted that the strains thus obtained were those due to the outside wires only, while the corresponding stresses were calculated for the total area of the cable under test. After a number of cables had been tested, a comparison of the results obtained with those of the single wire tests showed great differences. In nearly every case the limit of proportionality and the value of Young's modulus obtained for the cables were much higher and lower respectively than those obtained for the single wires. At the same time the regularity of the plotted points shows that the results obtained are the true strains for the outside wires and indicate that the stress distribution across the cable is not uniform. It was thought that if the loading was repeated a sufficient number of times the value obtained for the modulus would, perhaps, tend to approach the true value for the material of which the cable was composed. Accordingly, for the remainder of the cables, the modulus was determined for the first, second, third, fourth, fifth and tenth loadings.

The results show that the modulus under successive loadings tended to approach a limiting maximum value, but in the majority of cables tested, this limiting value was much below the true values of the material of which the cable was composed.

The results of the tests on long lengths of cable reveal some interesting facts on this point, and seem to indicate that the values of the limit of proportionality and modulus obtained by tensile tests on short lengths of cables are unreliable and inaccurate.

*Results.*—Table 11 gives the values obtained on the short cables for the limit of proportionality and Young's modulus under successive loadings. The results of similar tests on the single wires supplied separately are included for comparison.

Representative load-extension curves obtained are shown in Figs. 3 and 4.

TABLE 10.

*Tensile Strength of Short Cables and their Constituent Wires and of Single Wires supplied separately.*

| Column 1 |  |  |  |  | Column 2 | Column 3 |  |  | Column 4 | Column |
|---|---|---|---|---|---|---|---|---|---|---|
| Tests on Short Cables |  |  |  |  | Tests on Constituent Wires. | Tests on Single Wires supplied separately |  |  |  |  |
| Sample | N.P.L. Mark | Maker | Type | Ultimate Stress of Cable, tons per sq. in. | Ultimate Stress of Wires Forming Cable, tons per sq. in. | Maker | Diameter, inch | Ultimate Stress, tons per sq. in. | Efficiency on Constituent Wires, per cent | Efficiency on Single Wire, per cent |
| 30 tons | AKR4A | F | 7/·080 | 31·8 | 29·9 | F | 0·080 | 28·6 | 106 | 111 |
|  | AKR4B | F | 7/·128 | 29·2 | 29·8 | F | 0·128 | 28·1 | 98 | 104 |
|  | AKR4C | F | 4/·160 | 33·2 | 32·3 | F | 0·160 | 36·6 | 103 | 91 |
|  | AKR4D | F | 7/·160 | 33·2 | 33·6 | F | 0·160 | 36·6 | 99 | 91 |
|  | AKR4E | F | 19/·160 | 33·5 | 34·5 | F | 0·160 | 36·6 | 97 | 92 |
| 40 tons | AKR4F | F | 7/·080 | 45·2 | 48·2 | F | 0·080 | 49·2 | 94 | 92 |
|  | AKR4G | F | 7/·128 | 43·6 | 43·1 | F | 0·128 | 46·5 | 101 | 94 |
|  | AKR4H | F | 4/·160 | 38·4 | 39·6 | F | 0·160 | 53·4 | 97 | 72 |
|  | AKR4I | F | 7/·160 | 38·2 | 38·9 | F | 0·160 | 53·4 | 98 | 72 |
|  | AKR4J | F | 19/·160 | 38·0 | 39·5 | F | 0·160 | 53·4 | 96 | 71 |
| 60 tons | AKR4K | F | 7/·064 | 70·1 | 70·1 | F | 0·064 | 68·3 | 100 | 102 |
|  | AKR4L | F | 7/·080 | 73·9 | 72·2 | F | 0·080 | 71·2 | 102 | 104 |
|  | AKR4M | F | 7/·128 | 68·4 | 69·2 | F | 0·128 | 55·8 | 99 | 122 |
| 30 tons | AKS4A | G | 7/·080 | 52·4 | 52·9 | G | 0·080 | 55·6 | 99 | 94 |
|  | AKS4B | G | 7/·128 | 65·3 | 66·4 | G | 0·128 (30 ton) | 27·9 | 98 | 26 |
|  |  |  |  |  |  |  | 0·128 (60 ton) | 62·2 | — | 105 |
|  | AKS4C | G | 4/·160 | 38·1 | 35·7 | G | 0·160 | 40·0 | 107 | 95 |
|  | AKS4D | G | 7/·160 | 36·7 | 37·1 | G | 0·160 | 40·0 | 99 | 92 |
|  | AKS4E | G | 19/·160 | 43·5 | 44·8 | G | 0·160 (30 ton) | 40·0 | 97 | 109 |
|  |  |  |  |  |  |  | 0·160 (40 ton) | 49·3 | — | 88 |
| 40 tons | AKS4F | G | 7/·080 | 50·8 | 53·1 | G | 0·080 | 51·6 | 96 | 98 |
|  | AKS4G | G | 7/·128 | 47·4 | 48·2 | G | 0·128 | 49·7 | 98 | 95 |
|  | AKS4H | G | 4/·160 | 43·5 | 44·0 | G | 0·160 | 49·3 | 99 | 88 |
|  | AKS4I | G | 7/·160 | 40·8 | 41·1 | G | 0·160 | 49·3 | 99 | 83 |
|  | AKS4J | G | 19/·160 | 37·2 | 38·4 | G | 0·160 (40 ton) | 49·3 | 97 | 76 |
|  |  |  |  |  |  |  | 0·160 (30 ton) | 40·0 | — | 93 |
| 60 tons | AKS4K | G | 7/·064 | 68·1 | 65·0 | G | 0·064 | 61·6 | 105 | 110 |
|  | AKS4L | G | 7/·080 | 74·3 | 75·9 | G | 0·080 | 75·2 | 98 | 99 |
|  | AKS4M | G | 7/·128 | 29·7 | 29·5 | G | 0·128 (30 ton) | 27·9 | 101 | 106 |
|  |  |  |  |  |  |  | 0·128 (60 ton) | 62·2 | — | 48 |

## III. MECHANICAL TESTS ON LONG STRANDED CABLES.

Details of the stranded cables on which the tests were carried out are given in Table 8 in Section II.

It was decided that tests should be carried out on four long galvanized steel cables only. These were selected, as representative, from those cables submitted by the maker whose material had given consistent results under the tests carried out on single wires and on short lengths of cables.

The tests required were the determination of Young's Modulus ($E$) under tensile loading, employing a test length of 100 yards.

The tests were carried out as described in Technical Report upon Tests on Hard Drawn Copper Wires and Cables for Overhead Transmission Lines, Ref. F/T5.

## TABLE 11.

*Limit of Proportionality and Young's Modulus for Short Cables and for Single Wires supplied separately.*

| Tests on Short Cables | | | | | | | | | | | | | Tests on Single Wires supplied separately | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | N.P.L. Mark | Maker | Type | Sectional Area, sq. in. | Primitive Limit of Proportionality | | Modulus (*E*), lb. per sq. in. × 10⁻⁶ | | | | | | Maker | Diameter, in. | Stress at Limit of Proportionality, tons per sq. in. | Modulus (*E*), lb. per sq. in. × 10⁻⁶ | |
| | | | | | Load, tons | Stress, tons per sq. in. | 1st | 2nd | 3rd | 4th | 5th | 10th | | | | 1st | 2nd |
| 30 tons | AKR4A | F | 7/·080 | 0·0365 | 0·54 | 14·8 | 24·1 | 25·0 | — | — | — | — | F | 0·080 | 8·4 | 26·3 | 27·2 |
| | AKR4B | F | 7/·128 | 0·0889 | 1·40 | 15·7 | 24·6 | 25·0 | — | — | — | — | F | 0·128 | 6·8 | 27·0 | 27·5 |
| | AKR4C | F | 4/·160 | 0·0792 | 0·95 | 12·0 | 18·9 | 25·3 | — | — | — | — | F | 0·160 | 16·6 | 28·0 | 28·3 |
| | AKR4D | F | 7/·160 | 0·1385 | 1·40 | 10·1 | 25·8 | 25·8 | 25·0 | 25·5 | 25·1 | 25·3 | F | 0·160 | 16·6 | 28·0 | 28·3 |
| | AKR4E | F | 19/·160 | 0·3793 | 4·90 | 12·9 | 15·6 | 22·2 | 22·7 | 22·7 | 22·8 | 23·1 | F | 0·160 | 16·6 | 28·0 | 28·3 |
| 40 tons | AKR4F | F | 7/·080 | 0·0361 | 0·50 | 13·9 | 23·1 | 25·9 | — | — | — | — | F | 0·080 | 12·7 | 28·2 | 28·7 |
| | AKR4G | F | 7/·128 | 0·0905 | 1·95 | 21·6 | 18·2 | 25·1 | — | — | — | — | F | 0·128 | 10·6 | 27·7 | 28·3 |
| | AKR4H | F | 4/·160 | 0·0814 | 1·40 | 17·2 | 18·0 | 24·7 | — | — | — | — | F | 0·160 | 12·9 | 27·9 | 28·2 |
| | AKR4I | F | 7/·160 | 0·1443 | 2·20 | 15·3 | 18·2 | 24·2 | 23·4 | 23·2 | 23·6 | 23·5 | F | 0·160 | 12·9 | 27·9 | 28·2 |
| | AKR4J | F | 19/·160 | 0·3925 | 4·00 | 10·2 | 21·1 | 22·7 | 22·3 | 23·1 | 23·1 | 23·2 | F | 0·160 | 12·9 | 27·9 | 28·2 |
| 60 tons | AKR4K | F | 7/·064 | 0·0224 | 0·78 | 34·8 | 23·6 | 25·9 | — | — | — | — | F | 0·064 | 38·2 | 27·4 | 28·3 |
| | AKR4L | F | 7/·080 | 0·0352 | 0·95 | 27·0 | 22·1 | 26·0 | — | — | — | — | F | 0·080 | 17·7 | 28·9 | 29·3 |
| | AKR4M | F | 7/·128 | 0·0911 | 2·00 | 22·0 | 26·4 | 27·4 | — | — | — | — | F | 0·128 | 13·1 | 28·8 | 28·9 |
| 30 tons | AKS4A | G | 7/·080 | 0·0355 | 0·70 | 19·7 | 25·1 | 26·7 | — | — | — | — | G | 0·080 | 17·3 | 27·2 | 28·4 |
| | AKS4B | G | 7/·128 | 0·0879 | 2·10 | 23·9 | 21·7 | 25·6 | — | — | — | — | G | 0·128* | 20·3 | 28·5 | 29·1 |
| | AKS4C | G | 4/·160 | 0·0800 | 0·95 | 11·9 | 19·0 | 24·4 | — | — | — | — | G | 0·160 | 11·1 | 28·2 | 28·2 |
| | AKS4D | G | 7/·160 | 0·1363 | 2·0 | 14·7 | 23·0 | 25·6 | 25·7 | 25·8 | 25·9 | 25·7 | G | 0·160 | 11·1 | 28·2 | 28·2 |
| | AKS4E | G | 19/·160 | 0·3818 | 7·0 | 18·3 | 20·8 | 24·2 | 25·0 | 25·0 | 25·0 | 24·8 | G | 0·160 | 11·1 | 28·2 | 28·2 |
| 40 tons | AKS4F | G | 7/·080 | 0·0358 | 0·70 | 19·5 | 15·7 | 23·8 | — | — | — | — | G | 0·080 | 16·5 | 27·7 | 28·7 |
| | AKS4G | G | 7/·128 | 0·0903 | 1·80 | 19·9 | 26·1 | 27·3 | — | — | — | — | G | 0·128 | 10·4 | 27·6 | 28·7 |
| | AKS4H | G | 4/·160 | 0·0813 | 1·35 | 16·6 | 18·5 | 24·3 | — | — | — | — | G | 0·160 | 8·6 | 27·8 | 28·1 |
| | AKS4I | G | 7/·160 | 0·1410 | 2·00 | 14·2 | 20·3 | 24·5 | 24·1 | 24·1 | 24·2 | 24·2 | G | 0·160 | 8·6 | 27·8 | 28·1 |
| | AKS4J | G | 19/·160 | 0·3722 | 6·0 | 16·1 | 18·4 | 24·6 | 25·1 | 25·6 | 25·6 | 25·2 | G | 0·160† | 11·1 | 28·2 | 28·2 |
| 60 tons | AKS4K | G | 7/·064 | 0·0226 | 0·56 | 24·8 | 19·6 | 24·3 | — | — | — | — | G | 0·064 | 24·1 | 27·8 | 28·5 |
| | AKS4L | G | 7/·080 | 0·0374 | 1·25 | 33·5 | 21·3 | 23·5 | — | — | — | — | G | 0·080 | 25·2 | 28·4 | 29·2 |
| | AKS4M | G | 7/·128 | 0·0909 | 1·35 | 14·9 | 16·1 | 25·1 | — | — | — | — | G | 0·128† | 10·4 | 27·7 | 28·1 |

* The nominal strength of this wire was 60 tons per sq. in.

† The nominal strength of this wire was 30 tons per sq. in.

The results of the tests are given in Table 12. The limit of proportionality and modulus for the single wires are included for comparison.

The maximum safe load for the dynamometer (3·8 tons) was insufficient to reveal the limit of proportionality of cable No. AKR4E.

The limit of proportionality of cable No. AKR4L was masked by other strains.

TABLE 12.

*Limit of Proportionality and Young's Modulus for* 100-*yard Lengths of Cables.*

| | | | | |
|---|---|---|---|---|
| Sample | 30 tons | 30 tons | 30 tons | 60 tons |
| N.P.L. mark | AKR4A | AKR4C | AKR4E | AKR4L |
| Maker | F | F | F | F |
| Type | 7/·080 | 4/·160 | 19/·160 | 7/·080 |
| Sectional area, square inch | 0·0365 | 0·0792 | 0·3793 | 0·0352 |
| Load at limit of proportionality, tons | 0·313 | 1·09 | — | — |
| Stress at limit of proportionality, tons per square inch | 8·6 | 13·8 | — | — |
| Modulus ($E$), lb. per square inch $\times 10^{-6}$:— | | | | |
| 1st loading | 26·0 | 27·9 | 23·1 | 22·1 |
| 2nd loading | 25·2 | 27·5 | 25·0 | 27·4 |
| 3rd loading | 26·0 | 28·6 | 28·2 | 28·2 |
| 4th loading | 26·0 | 28·2 | 26·7 | 28·6 |
| 5th loading | 26·0 | 28·6 | 28·5 | 28·7 |
| Temperature during test, ° C. | 11½ | 15 | 15 | 5 |

*Tests of Single Wires supplied separately for comparison.*

| | | | | |
|---|---|---|---|---|
| Maker | F | F | F | F |
| Diameter, inch | 0·080 | 0·160 | 0·160 | 0·080 |
| Stress at limit of proportionality, tons per square inch | 8·4 | 16·6 | 16·6 | 17·7 |
| Modulus ($E$), lb. per square inch $\times 10^{-6}$:— | | | | |
| 1st loading | 26·3 | 28·0 | 28·0 | 28·9 |
| 2nd loading | 27·2 | 28·3 | 28·3 | 29·3 |

TABLE 13.

*Alteration of Modulus of* 100-*yard Lengths of Cables by Repeated Loadings.*

| N.P.L. Mark | Maker and Nominal Strength, tons per sq. in. | Type of Cable | Modulus of Elasticity, lb. per sq. in. | | Ratio $\frac{A}{B}$, per cent | Percentage of Breaking Load Applied |
|---|---|---|---|---|---|---|
| | | | A, 1st Loading | B, 5th Loading | | |
| AKR4A | F 30 | 7/·080 | $26\cdot0 \times 10^6$ | $26\cdot0 \times 10^6$ | 100 | 39 |
| AKR4C | F 30 | 4/·160 | $27\cdot9 \times 10^6$ | $28\cdot6 \times 10^6$ | 98 | 54 |
| AKR4E | F 30 | 19/·160 | $23\cdot1 \times 10^6$ | $28\cdot5 \times 10^6$ | 81 | 30 |
| AKR4L | F 60 | 7/·080 | $22\cdot1 \times 10^6$ | $28\cdot7 \times 10^6$ | 77 | 27 |

A typical load-extension diagram is shown in Fig. 5.

To ascertain the amount of increase of the modulus of elasticity due to repeated loadings, the loading of the cables was carried out five times, and the modulus of elasticity obtained for each loading. In most cases the load applied during the second and subsequent loadings was above the primitive limit of proportionality. The effect of repeated loading is seen from the results given in Table 13.

## IV. PITCH AND LAY OF CONSTITUENT WIRES OF LONG STRANDED CABLES.

The data given in Table 14 refer to the long stranded cables on which the tensile tests were made :—

Column 1 gives particulars of the cable.

Column 2 gives the mean diameters of the layers of constituent wires ; *a*, *b* referring to the layers commencing from the outside.

Column 3 gives the measured pitch of the wires.

Column 4 gives the calculated lay where

$$\text{lay} = \frac{\text{measured pitch}}{\text{mean diameter of layer of wires}}$$

NOTE.—The suffixes R and L refer to right-hand and left-hand winding respectively.

TABLE 14.

*Pitch and Lay of Constituent Wires of 100-yard Lengths of Cables.*

| Column 1 | | | Column 2 | | Column 3 | | Column 4 | |
|---|---|---|---|---|---|---|---|---|
| N.P.L. | Maker and Nominal Strength, tons per sq. in. | Type of Cable | Measured Pitch, Diameter, in. | | Measured Pitch of Wires, in. | | Lay of Wires | |
| | | | *a* | *b* | *A* | *B* | $\frac{A}{a}$ | $\frac{B}{b}$ |
| AKR4A | F 30 | 7/·080 | 0·170 | — | $3\frac{3}{4}$ L | — | 22 L | — |
| AKR4C | F 30 | 4/·160 | 0·247 | — | $7\frac{1}{2}$ L | — | $30\frac{1}{2}$ L | — |
| AKR4E | F 30 | 19/·160 | 0·667 | 0·342 | 8 L | 4 L | 12 L | $11\frac{1}{2}$ L |
| AKR4L | F 60 | 7/·080 | 0·170 | — | $3\frac{3}{4}$ L | — | 22 L | — |

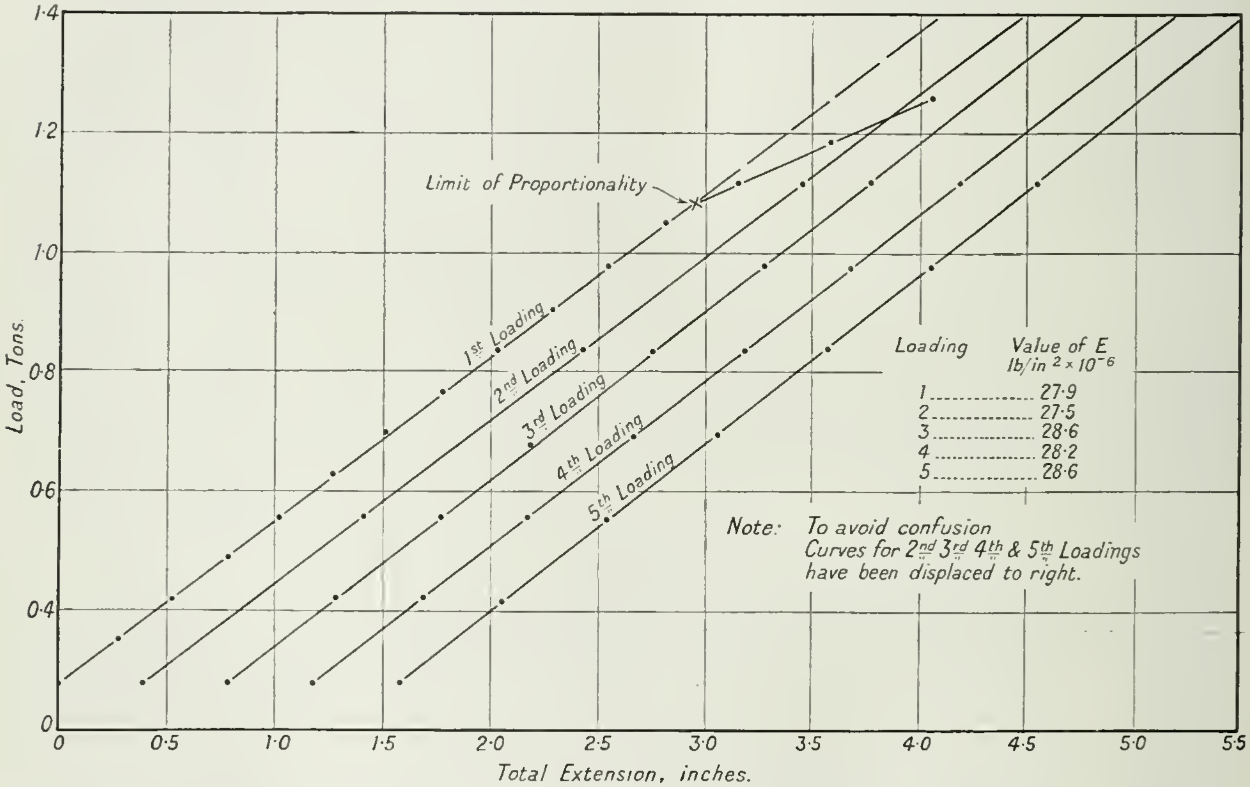


FIG. 5.—Typical Load-Extension Curves of 100-yard Lengths of Cables (4/·160).

# REPORT UPON TESTS ON STEEL-CORED ALUMINIUM CABLES FOR OVERHEAD TRANSMISSION LINES.

[REPORT (REF. F/T13) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

CONTENTS.

| | Page |
|---|---|
| Introduction .. .. .. .. .. .. | 1041 |
| Tensile Tests .. .. .. .. .. | 1041 |
| Limit of Proportionality .. .. .. .. | 1042 |
| Modulus of Elasticity .. .. .. .. | 1043 |
| Conclusions .. .. .. .. .. .. | 1043 |

## INTRODUCTION.

In the preparation of specifications for overhead transmission line materials by the British Engineering Standards Association, it was found that there was a lack of information as to the mechanical properties of bare steel-cored aluminium cables.

Tests were carried out at the National Physical Laboratory on two samples of seven-wire strand, each consisting of a central galvanized steel wire approximately 0·146 inch in diameter with six aluminium wires of equal diameter laid round it. The chief difference between the two samples was that the steel core of one was of considerably higher tensile strength than that of the other.

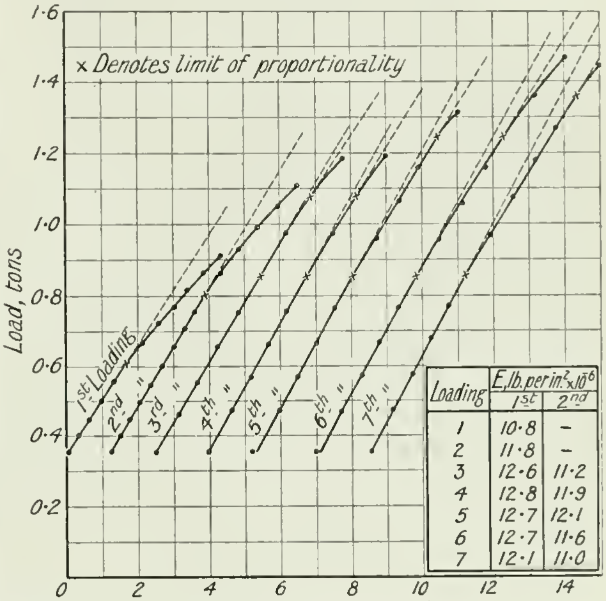
In view of the results obtained on stranded copper and aluminium conductors (see Technical Reports, Ref. F/T5 and Ref. F/T6),* the tests were carried out on lengths of 100 yards as well as on short lengths of cable and individual wires. Further tests were made on short specimens of cable and on individual wires cut from one of the 100-yard samples after the latter had been subjected to prolonged straining at a load of 3 050 lb. and after an interval of rest of 157 days. In this report, these different specimens are distinguished as "Cable 1," "Cable 2" and "Cable 2 after straining."

## TENSILE TESTS.

Tensile tests were carried out on short lengths of cable (4 ft.) and on the constituent wires, and the results are given in Table 1.

The mechanical efficiency of the cables, defined as the breaking load of the cable divided by the sum of the breaking loads of the constituent wires, is calculated to be 93 per cent, 93·2 per cent and 94·6 per cent for the three specimens respectively. These values are interesting, in view of the wide difference between the physical properties of the component metals. In all cases, it was found that the aluminium wires broke first, the whole of the load then being thrown upon the steel core, which at once pulled through the grips. It should be remarked that the load on the cable, when the aluminium wires broke, greatly exceeded the breaking load of the steel core, so that, had the latter not pulled through, it must have broken. The load at which the aluminium wires broke is consequently the true ultimate strength of the cable.

Previous experiments on aluminium cables (Technical Report, Ref. F/T6) showed that the mechanical efficiency of a seven-wire cable was approximately 98 per cent. If it is assumed that, when a steel-cored aluminium cable is broken, the total load on the aluminium wires is 98 per cent of the sum of the breaking loads of the individual aluminium wires, an estimate may be made of the load on the steel core at the instant of fracture, and hence an approximate formula may be derived for estimating the strength of the composite cable from known particulars of the components. These calculations are summarized in Table 2.



NOTE:–
Between the 5th & 6th loadings the cable was subjected to a load of 3050 lbs. for 8 days continuously and then allowed to rest for 157 days.
To avoid confusion, curves for 2nd, 3rd, 4th, 5th, 6th & 7th loadings have been displaced to the right.

Load-extension curves of steel-cored aluminium cable (Cable 2).

From the values given in Table 2, it would appear that the breaking load of a steel-cored aluminium cable would not be less than 98 per cent of the sum of the breaking loads of the aluminium wires plus 85 per cent of the breaking load of the steel core, and that when the cable has been erected and has been subjected to repetitions of stress, the mechanical efficiency is increased. For the purpose of calculation, it might be desirable to take the average of the three values, i.e. 89 per cent, as the efficiency of the steel.

---

* *Journal I.E.E.*, 1923, vol. 61, pages 997 and 1013.

TABLE 1.

*Tensile Tests on Short Lengths of Cable and on Constituent Wires.*

| | Diameter | Tensile strength | | Extension |
|---|---|---|---|---|
| | inch | tons | tons per sq. in. | per cent |
| *Cable* 1. | | | | |
| Complete cable .. .. .. .. .. | 0·438 | 1·93 | 16·4 | — |
| Steel wire.. .. .. .. .. .. | 0·147 | 0·886 | 52·2 | — |
| Aluminium wire (average) .. .. .. | 0·146 | 0·198 | 11·9 | — |
| Sum of all six aluminium wires .. .. | — | 1·194 | 11·9 | — |
| *Cable* 2. | | | | |
| Complete cable .. .. .. .. .. | 0·434 | 2·28 | 19·8 | 2·3 (on 8 in.) |
| Steel wire.. .. .. .. .. .. | 0·143 | 1·34 | 83·3 | 6·5 (on 2 in.) |
| Steel wire (galvanizing removed) .. .. | 0·137 | 1·30 | 88·2 | 7·0 (on 2 in.) |
| Aluminium wire (average) .. .. .. | 0·145 | 0·184 | 11·2 | 5·2 (on 2 in.) |
| Sum of all six aluminium wires .. .. | — | 1·102 | 11·2 | — |
| *Cable 2 after straining.* | | | | |
| Complete cable .. .. .. .. .. | 0·433 | 2·28 | 19·8 | 2·0 (on 8 in.) |
| Steel wire.. .. .. .. .. .. | 0·143 | 1·32 | 82·2 | 6·0 (on 2 in.) |
| Steel wire (galvanizing removed) .. .. | 0·135 | 1·21 | 84·6 | — |
| Aluminium wire (average) .. .. .. | 0·145 | 0·181 | 11·0 | 5·4 (on 2 in.) |
| Sum of all six aluminium wires .. .. | — | 1·085 | 11·0 | — |

### LIMIT OF PROPORTIONALITY.

As in the case of copper and aluminium cables, the limit of proportionality of a steel-cored aluminium cable is not a fixed value but is raised by increasing the loading. The results of a series of tests on a 100-yards length of Cable 2 are shown in the diagram on page 1041. It will be noticed that after the second loading the load-extension diagrams are similar. The curve is a straight line up to a definite limit of proportionality, and after this has been passed the curve again becomes a straight line terminated by a second limit of proportionality. The first limit of proportionality is quickly raised to 1 917 lb., corresponding to 39 per cent of the breaking load of the cable, and subsequent loadings have no effect on this value. This first limit of proportionality is, however, of less practical importance than the second, the value of which is steadily raised by increased loading. By this means the second limit of proportionality was raised to 3 050 lb., corresponding to 60 per cent of the ultimate load of the cable.

TABLE 2.

*Determination of the Strength of a Composite Cable from the Strength of the Components.*

| | Cable 1 | Cable 2 | Cable 2 after straining |
|---|---|---|---|
| | tons | tons | tons |
| Breaking load of cable (*a*) | 1·93 | 2·28 | 2·28 |
| 98 per cent of sum of breaking loads of aluminium wires (*b*) .. | 1·17 | 1·08 | 1·062 |
| Load taken by steel at instant of fracture [i.e. (*a*) — (*b*)] .. .. | 0·76 | 1·20 | 1·218 |
| Breaking load of steel wire | 0·886 | 1·34 | 1·32 |
| Percentage of load on steel at failure of cable .. | 85·8 | 88·5 | 92·3 |

This load was maintained on the cable for eight days, and additional stress-strain curves were afterwards obtained with two further cycles of loading, the results of which are also shown in the diagram. No abnormal features are noticeable, and the results indicate that the cable is still mechanically sound.

The results of the tensile tests on specimens cut from Cable 2, after straining, are given in Table 1. It will be observed that, as regards the ultimate strength and percentage extension of the cable and of the individual wires, the repetition of stress on the cable and the prolonged application of a load exceeding half the breaking load have had no deleterious effect, these properties, both for the steel and aluminium and for the complete cable, being practically unaltered.

The values of the limit of proportionality and modulus of elasticity are given in Table 3 and show that, in respect of these properties also, the steel is unaffected, but that the limit of proportionality of the aluminium wires has been increased and the modulus decreased. These results indicate that the aluminium wires have received a permanent set, and it may be assumed that this is the normal operating condition of this class of cable. This suggests the desirability, already noted with copper and aluminium cables, of pulling up a steel-cored cable very taut when erecting, before finally adjusting the sag, in order to give the aluminium strands the necessary permanent set, and thus assure the constancy of behaviour of the cable within the limits of loading. This initial load may be as high as 60 per cent of the ultimate strength of the cable.

TABLE 3.

*Limit of Proportionality and Modulus of Elasticity of Constituent Wires of Cable 2.*

| | Wire from Cable 2 as received | | Wire from Cable 2 after straining | |
|---|---|---|---|---|
| | Limit of proportionality | Modulus of elasticity | Limit of proportionality | Modulus of elasticity |
| | tons per sq. in. | lb. per sq. in. | tons per sq. in. | lb. per sq. in. |
| Aluminium | 2·58 | $9 \cdot 42 \times 10^6$<br>$9 \cdot 79 \times 10^6$ | 3·34 | $8 \cdot 36 \times 10^6$<br>$9 \cdot 02 \times 10^6$ |
| Steel .. | 27·8 | $28 \cdot 8 \times 10^6$ | 27·6 | $29 \cdot 9 \times 10^6$ |

It should be noted that the permanent elongation of the aluminium wires was small, and that the specimen showed no tendency to "bird cage" on the removal of the load.

### MODULUS OF ELASTICITY.

The tests on the long lengths of cable show that, as with copper and aluminium cables, the modulus of elasticity increases with repetition of loading up to a maximum. In the tests on Cable 1, in which the maximum loads applied did not greatly exceed the primitive limit of proportionality, the modulus of elasticity increased to $12 \cdot 7 \times 10^6$ lb. per sq. in. It is interesting to note that the value of the modulus as calculated on the assumption that the cable behaves as a compound bar in which the strains of both materials are equal, and that the stresses are proportional to the moduli of the component metals, is $12 \cdot 6 \times 10^6$ lb. per sq. in.

In the case of Cable 2, repeated loadings up to the first limit of proportionality gave a value of the modulus of $12 \cdot 7 \times 10^6$ lb. per sq. in. as shown in the diagram, the calculated value from the moduli of the constituent wires being $12 \cdot 5 \times 10^6$ lb. per sq. in.

After the first limit of proportionality the cable stretched with a somewhat smaller modulus, varying from $11 \cdot 0 \times 10^6$ to $12 \cdot 1 \times 10^6$ lb. per sq. in.

### CONCLUSIONS.

This type of cable behaves similarly to a homogeneous copper or aluminium cable, its tensile strength closely approaching the sum of the breaking strengths of the constituent wires, and its limit of proportionality increasing with repeated increasing loads. The limit of proportionality may be safely raised by this means to at least 60 per cent of the breaking load of the cable.

With a seven-wire strand the breaking strength may safely be taken as 93 per cent of the sum of the strengths of all the wires. A more general rule which it is suggested may apply to steel-cored aluminium cables having more than seven wires, is to assume that the breaking strength is 98 per cent of the sum of the breaking loads of the aluminium wires plus 89 per cent of the sum of the breaking loads of the steel wires.

For the purpose of overhead line calculations the modulus of elasticity may be computed on the assumption that the stresses in the two materials will be proportional to their moduli of elasticity. The value of the modulus of elasticity of the aluminium wires is consistent with the values obtained from tests on single wires of other diameters (see Technical Report Ref. F/T6).

# ELECTRIC LINE CALCULATIONS: THEIR PRACTICAL APPLICATION TO TRANSMISSION AND DISTRIBUTION PROBLEMS.

By W. T. J. Atkins, B.Sc.(Eng.), Student.

(Abstract *of paper read before the* North Midland Students' Section, *27th March*, 1923.)

Summary.

The type of network usually found in practice, i.e. one feeding scattered loads and having a complicated lay-out, is nearly always neglected, or at best receives summary treatment, in literature dealing with the subject of line calculations.

The fundamental principles are here briefly reviewed, and methods based on the principle of superposition are described, enabling problems of any degree of complexity to be solved by successive approximation.

The work involved in the solution is much less than that necessitated by a direct method, as the limits of accuracy of the data are generally fairly wide.

The calculation of short-circuit currents and of their heating effect is also described and examples are given.

## I. Fundamental Principles.

The E.M.F. and current at one end of any uniform system of parallel conductors are related to the E.M.F. and current at the other end by the expressions

$$E = AE_0 \pm BI_0\,; \quad I = AI_0 \pm CE_0$$

$A$, $B$ and $C$ are complex operators or ratios, i.e. quantities of the same type as impedance or admittance, and consequently the line can be replaced, for calculation purposes, by a system of concentrated or "lumped" impedances and admittances which will be its exact electrical equivalent.

The most useful of such substitutions is given by replacing the actual impedance, $Z$, by

$$Z\left(1 + \frac{ZY}{3\,!} + \frac{Z^2Y^2}{5\,!} + \dots\right)$$

and the admittance, $Y$, by two admittances, one at each end, the value of each being

$$\left(\frac{ZY}{2\,!} + \frac{Z^2Y^2}{4\,!} + \dots\right) \Big/ Z\left(1 + \frac{ZY}{3\,!} + \frac{Z^2Y^2}{5\,!} + \dots\right)$$

It follows that every electrical transmission system may be replaced by a network. This statement, as will be shown later, is subject to considerable qualification, but for the present it will be assumed to be true.

The problem of calculating the electrical quantities in any network composed of conductors of which the E.M.F./current ratios do not vary in any circumstances, admits of rigorous solution by the application of Kirchhoff's laws and the solution of the resulting simultaneous equations.

Further, it is a direct consequence of the linearity of the fundamental differential equations of such a circuit that the phenomena resulting from any particular cause (e.g. an E.M.F. applied between two points) are entirely independent of the phenomena resulting from all other simultaneous causes (E.M.F.'s) and may be superposed on the latter, so that the total of the effects in the network, each of which may be separately calculated from its own cause, correctly represents the effect of all the causes acting in conjunction.

It also follows that the variation of an electrical quantity at one point causes a linear variation of the electrical quantities at some or all of the other points in the network, which variation may be calculated without regard to any other existing circumstances. This principle, with slight modifications, is of great practical utility.

## II. Limitations of Network Calculations.

The foregoing theory is based upon assumptions which are not justified in most practical cases, therefore it becomes necessary to examine the conditions arising in existing distributing systems, in order that the methods employed may be modified so as to avoid the errors (which might in some cases be extremely great) involved in neglecting the violation of the assumptions on which the calculation is based.

These assumptions are :—

(*a*) That the "steady state" has been attained.

(*b*) That loads and line constants may be represented as ratios of E.M.F. to current which are independent of the absolute values of those quantities and also of the frequency.

(*c*) That the wave-form in the alternating-current case is a pure sine-wave.

(*d*) That the currents have no reaction on the applied E.M.F.'s.

(*a*) The "steady state" will always exist in the absence of abnormal conditions, which are dealt with later.

(*b*) The resistance or impedance of any conductor or piece of apparatus may be defined as the ratio of the E.M.F. across it to the current flowing through it, and hence it is by no means correct, in general, to represent a load in this way. A more correct representation is given by the product of E.M.F. and current, but even this is of doubtful validity, and in any case is impracticable as it leads to cumbrous quadratic equations.

It is clear that the "constants" of both loads and lines are complicated functions of the frequency.

(*c*) If E.M.F.'s containing harmonics in addition to the fundamental wave are impressed upon a network, or even upon a single impedance, and the currents are calculated from the "equivalent sine-waves" of the E.M.F.'s, the values so obtained are not, in general, equal to the "equivalent sine-currents." This is especially the case where apparatus with negative reactance (e.g. static condensers for power factor correction) is in circuit, as the harmonic components of the currents are disproportionately magnified. The legitimate method of dealing with this case is to split up the E.M.F. wave into its components, calculate the resulting currents separately, and recombine them in accordance with the principle of superposition. Since the wave-shape of modern alternators closely approximates to the sine-wave, only the fundamentals will here be considered.

(*d*) The applied E.M.F.'s, i.e. the busbar voltages of the generating stations, will normally be artificially adjusted to a constant value, or raised to compensate in some degree for the regulation of the mains, etc.

### III. The Art of Approximation.

It is evident that no form of direct mathematical analysis can be devised to take into account all the factors bearing on the problem without being excessively complicated. Methods of approximation must therefore be substituted; but it should be clearly understood that this does not imply a lesser degree of accuracy in the result. The method of successive approximation, or "trial and error," is capable of yielding results to any desired degree of accuracy with far less labour than the direct method in problems of this nature, and is not in any sense confined to its usually accepted meaning among engineers.

The considerations which limit the extent of the calculations are: (*a*) the accuracy of the data, and (*b*) the desired accuracy of the result. Only (*a*) will be examined in detail here, as (*b*) is merely a matter of additional arithmetic.

*Line constants.*—The calculation of the line constants is based on the effective resistance, etc., per unit length, i.e. on the E.M.F./current ratios which actually obtain under service conditions. It is the author's opinion that ± 5 per cent are the narrowest limits within which such figures can justifiably be placed if they are calculated from the dimensions of the conductors, etc. The alternative of measurement would be rather difficult and scarcely more accurate except in the case of an extremely long line.

The calculation of the "lumped" constants from the expressions given presents no difficulty and, in fact, will usually merely involve taking the first terms only in each case.

*Loads.*—It is generally with regard to the loading, or assumed loading, of any network that the most serious limitation is placed on the calculation. In addition to the uncertainty which may exist as to the values of the loads themselves, the diversity factor, in so far as it affects the incidence of the loads where their positions are scattered, and the individual power factors in the a.c. case, so greatly affect the regulation of, and the current distribution among the mains, that it is often only possible to discover the "best" and "worst" conditions in any particular instance.

### IV. Classification of Problems.

The problems encountered in practice may arbitrarily be divided into four classes, which, in order of complexity, are:—

(1) Single untapped line supplying load.
(2) Single line with tapped loading.
(3) Networks fed from a single point and loaded in any way.
(4) Networks loaded in any way, but fed from two or more points.

These cases will be considered in order.

(1) *Single untapped line.*—So much has been written on this form of transmission that it will be sufficient to remark that it is more convenient in practice to use the fundamental equations rather than the equivalent circuits.

(2) *Single line with tapped loading.*—This case and the following ones are much more frequently met with than (1), and will therefore receive greater attention.

The first step is to determine the equivalent admittances to be placed at the ends of each section of the line. These will often be negligible, but with comparatively long lengths of cable they may considerably affect the results, and must therefore be taken into account.

After a little experience, an intelligent guess may next be made as to the voltage at each point of the line, and this enables the load currents to be found approximately. Since the line admittances have been calculated for the ends of each section, the resulting currents, which are deduced from the assumed voltages, may be added directly to the load currents, in order to obtain the total currents flowing in the sections.

The voltage drop in each section for these currents may now be worked out, and it will, in general, be found that the voltages so obtained differ by small amounts from those originally guessed. In consequence of this, the load currents must be corrected in order that the loads (in kVA) may have the values given. This process is assumed not to affect the voltages. This, of course, is not the case; but the important point is that the changes in the voltages so produced are of the next lower order of small quantities. The additional currents (not the corrected currents) are now assumed to flow, and the additional drops thereby caused are calculated. (This is justified by the principle of superposition.) The corresponding current increments are again of the next lower order of small quantities, and so on.

The advantages of performing the calculation in this way are that each stage merely involves simple arithmetic, and that the calculation is less laborious than the direct method, for it can readily be determined by inspection when the desired degree of accuracy has been obtained.

There are many cases, however, in which this method would be an unnecessary refinement. To deal with these cases, use may be made of the fact that the drop in a given length of conductor for 1 ampere at a power factor of $\cos\phi$ is nearly

$$R\cos\phi + X\sin\phi$$

where $R$ is the resistance and $X$ the reactance. This expression neglects the component of the drop which is in quadrature with the applied voltage, and is only strictly true when $X/R = \tan\phi$, but it is a sufficient approximation to the algebraic drop when the latter does not exceed about 5 per cent.

It will be found useful, where many such calculations are contemplated, to draw up a table based on this approximation, of drops per 1 000 yards per 10,100 or 1 000 kVA, for the standard types of line employed.

(3) *Networks fed from a single point.*—The use of simultaneous equations in the first approximation is unavoidable. The working tends to become formidable if the network is at all complicated, and is most readily accomplished by determinants. After this first step has been taken, the remainder of the solution is carried out exactly as before. It is, of course, essential that the complete expressions for the drops be used for calculating all network problems, as the same algebraic voltage-drop may correspond to an infinite variety of "vectorial" drops and, therefore, of currents.

The process of successive approximation will generally be found to produce voltage differences between points which are actually electrically connected. This does not, however, invalidate the method or cause any practical difficulty, as all that is necessary is to superpose such a circulating current as will equalize the voltages in question. The value of the circulating current is simply the quotient of the voltage difference by the impedance of the current path.

(4) *Networks fed at more than one point.*—This case may be dealt with by a slight modification of the previous method.

The most convenient of the feeding-points is chosen, and it is assumed that all the loads are fed from that one point, and the first approximation worked out. Next, the loads are completely disregarded, and a set of tables of drops and currents is compiled for the other feeding points taken separately, on the assumption that each one sends a current equivalent to its actual share of the total load to the originally chosen feeding-point. The various drops and currents are then all superposed, and further approximation, if necessary, is carried out as before.

It is an easy matter to determine the operating characteristics (e.g. interchange of load and wattless currents) of such a system when once the problem has been solved in any particular case. All that is necessary is to assume everything except the quantities at two points to be constant, and add the effect of their variations to the existing conditions, correcting if necessary.

## V. Losses and Efficiency.

The line losses consist almost wholly of resistance losses if the load factor is reasonably high, the dielectric losses being then small in comparison. In any case, their calculation presents no difficulty, and may generally be most easily accomplished in the form

$$\Sigma I^2\delta r + \Sigma E^2\delta g$$

## VI. Abnormal Conditions.

Only the condition of short-circuit will be considered here.

The thorough investigation of the problem is very complex, because it necessarily has to be based on the electrical characteristics of the generating and transforming plant as well as those of the lines, and it is doubtful whether all of the physical quantities could be taken into account by ordinary mathematical methods.

Fortunately, however, the short-circuit current of modern generators may be approximated to by curves having fairly simple exponential laws, which are supported by much experimental evidence in the form of oscillograph records.

In the opinion of the author, the most practically useful form into which these curves have been put is the series of "American standard short-circuit factors" shown in Fig. 1. These show the factor by which the full-load current of any system, consisting of the generators and apparatus connected between them and the short-circuit, must be multiplied to obtain the short-circuit current in terms of time. The curves cover a wide range of values of total impedance, and this impedance is expressed as a percentage based on the capacity of the generators in circuit. What is meant is that, if normal full-load current flows, the impedance drop is the given percentage of the voltage of generation, so that

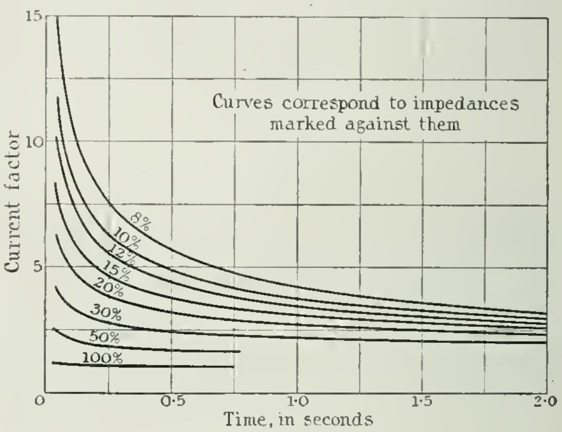


Fig. 1.

Percentage impedance

$$= (100\ VA/V^2)\ (\text{Impedance in ohms})$$

In order, therefore, to discover the short-circuit current at any point in a system, all that is necessary is to calculate the percentage impedance from, and including, the generators up to the point in question, when the value and time variation of the current may immediately be obtained. Of course, if the voltage is stepped up for transmission purposes, the impedance must be reduced to that corresponding to the voltage of generation, by dividing by the square of the ratio, exactly as is done for reducing secondary quantities to primary in the case of transformers, etc. Care must also be exercised where generators or mains are in parallel.

In addition to the problem of determining the necessary rupturing capacity of switchgear, the question of the minimum size of conductor that may safely be employed is one which often arises. The author has made a number of calculations based on the American curves and has found that, to a sufficient degree of approximation for this purpose, the current flowing from the instant of short-circuit for any reasonably short time (up to about 5 seconds) may be replaced, so far as its effective or "mean square" value is concerned, by an equivalent constant current flowing for the same time, the magnitude of which is the instantaneous value of the short-circuit current at one-quarter of the period in question. Fig. 2 shows some of the cases considered, and on which this approximation was based.

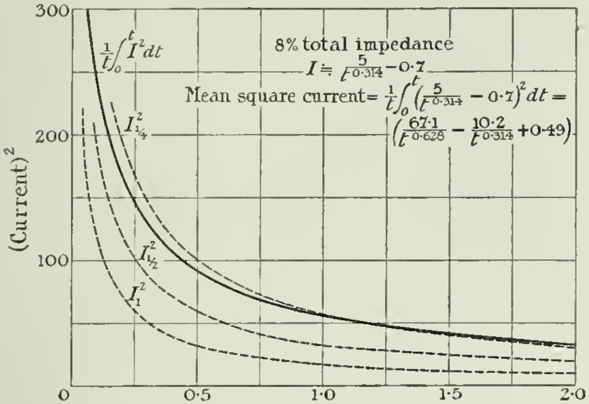


FIG. 2.

## VII. GENERAL REMARKS.

It is not claimed that the methods described in this paper have any particularly original features; they merely represent the method of practical application of first principles which the author has found most suited to his own point of view, and it has therefore not been considered advisable to go into great detail, as such matters vary with the ideas of the individual.

Line calculations are often highly complicated, although they only involve simple principles, and everything depends upon intelligent approximation. There is wide scope for mathematical ingenuity, but after a little practice a faculty of intuition is developed which is more to the point, and which enables intermediate steps to be omitted, with a considerable reduction of laborious "spade-work." The most important point is not to lose sight of the wood on account of the trees. In this connection, a rough graphical representation of the problem is useful in preserving a sense of proportion.

### EXAMPLE.

Fig. 3 shows diagrammatically a 33 kV three-phase network fed from the two power stations A and G. In practice, it would probably be more complicated, but it has been made comparatively simple, as the present purpose is to illustrate the principles involved in the calculation of its operating characteristics.

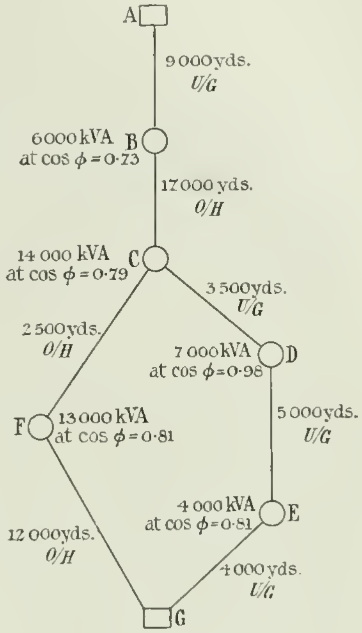


FIG. 3.

Line constants per 1 000 yards :—

Underground (Duplicate 0·1 sq. in. cable) :—

$$\begin{cases} Z = 0{\cdot}121 + 0{\cdot}052j \\ I_c = 0{\cdot}10 + 1{\cdot}90j \end{cases}$$

Overhead (Duplicate 3/0 S.W.G. Spacing 36 in.) :

$$\begin{cases} Z = 0{\cdot}112 + 0{\cdot}158j \\ I_c = 0{\cdot}12j \end{cases}$$

Total load current (42,000 kVA at $\cos\phi = 0{\cdot}85$)

$$\doteqdot 650 - 440j$$

With charging current $(1{\cdot}7 + 37j)$

$$\doteqdot 650 - 400j$$

Load on G = 30 000 kVA at $\cos\phi = 0{\cdot}83$

$$\frac{\text{Current GFC}}{\text{Current GEDC}} = \frac{0{\cdot}410 - 0{\cdot}083j}{0{\cdot}590 + 0{\cdot}083j}$$

The approximate load current is first found, and to this is added the total charging current of the network.

Assume all the loads to be fed from A.

Starting from A, the current in each section is determined by successively subtracting the load currents as each point of supply is passed.

On arriving at C, assume a current $I$ to flow via CF. Calculate the drops CFG and CDEG. These must be equal. A simple equation results from which $I$ is found.

The approximate currents in all the sections are now known (Table 1).

TABLE 1.

| Section | Amps. |
|---|---|
| AB | $650 - 400j$ |
| BC | $570 - 375j$ |
| CF | $190 - 150j$ |
| CD | $195 - 30j$ |
| DE | $70 - 15j$ |
| FE | $0 - 10j$ |

Now calculate the current corresponding to the load on G, and assume that it flows straight through to A without any being distributed en route. It is divided between the paths GFC and GEDC in the inverse ratio of their impedances.

The currents so found, added to those of Table 1, are shown in Table 2, and are the first approximation to the line currents.

TABLE 2.

| Section | Amps. | Drop |
|---|---|---|
| AB | $215 - 150j$ | $315 - 60j$ |
| BC | $135 - 55j$ | $410 + 255j$ |
| CF | $40 + 5j$ | $5 + 15j$ |
| FG | $-115 + 160j$ | $-460 - 5j$ |
| CD | $-85 + 105j$ | $-55 + 30j$ |
| DE | $-210 + 120j$ | $-155 + 15j$ |
| EG | $-280 + 145j$ | $-215 - 110j$ |

The drops CFG and CDEG for these currents are next worked out, and a difference $V$ is discovered. From the known impedance $Z$ of the ring CFGEDC, and this voltage, the circulating current necessary to rectify this is easily calculated $(I = V/Z)$.

Drop CFG $= -455 + 10j$.
Drop CDEG $= -425 - 65j$.
Difference $= 30 - 75j$.
Ring impedance $= 3{\cdot}07 + 3{\cdot}36j$.
$\therefore$ Circulating current $= -7{\cdot}8 - 16j\ (-10 - 15j)$.

The corrected currents and voltages are given in Table 3.

If it were desired, it would be a simple matter to continue the process of approximation to any degree of accuracy, but Table 3 is as near to the actual state of affairs as would probably be required in practice.

Suppose, now, it is required to find the effect of transferring current at any given power factor from one station to the other. All that is necessary is to calculate the drops produced by this current flowing straight through, subtract them from the existing voltages, and the new voltages will be obtained. The currents are also found by simple addition.

Total impedance (straight through) $= 3{\cdot}81 + 3{\cdot}93j$.

Drop for 10 000 kVA at $\cos\phi = 0{\cdot}7$ lag $(125 - 130j)$ transferred from one station to the other $= 985 - 5j$ volts, i.e. 1 700 volts drop between lines.

Again, if synchronous condensers were installed at C, their effect could be determined with great ease by imagining so much leading quadrature current to flow to C from A and G.

As an example of the calculation of short-circuit currents, suppose a short-circuit to occur at the point D, with generators of a total capacity of 50 000 kVA connected to the bars at A and G. The current fed into the fault passes through two paths in parallel: (*a*) GED, (*b*) ABC and GFC in parallel, and then CD. The total impedance is easily found to be $0{\cdot}616 + 0{\cdot}565j$ ohms.

Expressed as a percentage this is

$$(0{\cdot}616 + 0{\cdot}565j) \times 100 \times 50\,000 \times 1\,000/(33\,000)^2$$
$$= (0{\cdot}616 + 0{\cdot}565j) \times 4{\cdot}59 = 2{\cdot}8\,\% + 2{\cdot}6j\,\%$$

The probable impedance of generators and step-up transformers will be of the order of

$$2\,\% + 15j\,\%$$

making the total impedance

$$4{\cdot}8\,\% + 17{\cdot}6j\,\% = 18{\cdot}2\,\%$$

The short-circuit current (expressed as a multiple of the full-load current), may now be read directly off the curves.

At $0{\cdot}2$ second it is about $4{\cdot}3$ times full-load current, i.e. 215 000 kVA (4 000 amperes).

If the short-circuit were maintained for 5 seconds before being cleared, the heating in the conductors would be approximately the same as that produced by the short-circuit current at $1{\cdot}25$ seconds (2 600 amperes) flowing for 5 seconds, or, what is the same thing, 5 800 amperes flowing for 1 second.

TABLE 3.

| Section | Amps. | | P.F. | Drop | | Volts | |
|---|---|---|---|---|---|---|---|
| AB | $215 - 150j$ | 260 | 0·82 | $315 - 60j$ | B | $18\,735 + 60j$ | 32 500 |
| BC | $135 - 55j$ | 145 | 0·93 | $410 + 255j$ | C | $18\,325 - 195j$ | 31 800 |
| CF | $30 - 10j$ | 30 | 0·95 | $10 + 10j$ | F | $18\,315 - 205j$ | 31 800 |
| FG | $-125 + 145j$ | 190 | 0·65 | $-440 - 40j$ | G | $18\,755 - 165j$ | 32 500 |
| CD | $-75 + 120j$ | 140 | 0·53 | $-55 + 40j$ | D | $18\,380 - 235j$ | 31 800 |
| DE | $-200 + 135j$ | 240 | 0·83 | $-155 + 30j$ | E | $18\,535 - 265j$ | 32 100 |
| EG | $-270 + 160j$ | 315 | 0·89 | $-220 - 100j$ | G | $18\,755 - 165j$ | 32 500 |

# WIRELESS DIRECTION-FINDING IN STEEL SHIPS.

By C. E. Horton.

(*Paper received 1st May, and read before the* Wireless Section *6th June,* 1923.)

## Summary.

The problems of direction-finding which are peculiar to ships are discussed.

A method of regarding the action of a ship on wireless waves is given, as well as means of correcting for the deviations so produced.

The precautions to be observed in the calibration of a ship direction-finder are indicated.

A laboratory method of investigating the action of metal structures is described, and the use of multiple-aerial systems is considered.

To ascertain a ship's position at sea by means of directional wireless it is necessary to obtain the true bearing of at least two stations, the positions of which are known. Either the ship must make the observations herself or she must ask shore stations to take bearings while she transmits a suitable signal. The responsibility for the accuracy of the work rests, in the first case, with the ship and, in the second, with the shore stations.

There are some obvious advantages in having the direction finder located on board rather than on shore. For the ship is no longer dependent on shore direction-finding stations, which, in this country, are few and far between. It can make use of just those transmitting stations out of the large number now working which are most conveniently situated for obtaining an accurate fix of position; and there is no reason to restrict the work to one wave-length or one type of station. Consistent bearings of three or more stations give a far greater certainty to the result than is obtained by relying on two fixes only.

Again, an experienced operator can form an estimate of the reliability of any bearing which he obtains. He knows just how much to allow for such interference as he may have experienced. The captain of the ship can likewise form an estimate of the reliability of his apparatus and staff. Where the observations are taken by the ship the captain is therefore in a position to know how far to trust the figures submitted to him. Should a mistake occur the responsibility rests clearly with the ship.

These are great advantages which may at some future time reduce the need for shore direction-finding stations, and create a demand for suitable beacon stations in their stead. Unfortunately, the first requirement of a good direction-finding service, which is accuracy, is very much more difficult to achieve in a ship than on shore, where conditions are usually more favourable. The work about to be described is concerned with overcoming the special difficulties which arise in ships. These difficulties are roughly proportional to the size and congestion of the metal structures in the vicinity of the direction finder, and are therefore obtained to full perfection in a modern man-of-war.

The limitations to the accuracy of direction finders which arise from atmospheric effects or are due to the peculiarities of wave propagation over the earth will not here concern us. Only those disturbing factors which are especially characteristic of ship work will be considered.

## Calibration of a Ship Direction-finder.

To determine the direction of propagation of a train of electromagnetic waves one seeks to find the direction of the alternating magnetic and electric forces of the wave. Then for plane waves in an isotropic medium it is known that the direction of propagation is perpendicular to the plane containing the magnetic and electric forces. In the vicinity of a metal ship the magnetic and electric forces due to a wave passing over it will vary in direction and magnitude from point to point; at any particular point they will probably not be the same as the directions and magnitudes of the forces in the undisturbed parts of the field, i.e. at a considerable distance from the ship.

A satisfactory direction finder for use on a ship has to allow for this complication. It has to determine the directions of the forces appropriate to the undisturbed wave. Although it is necessary to determine the directions of both the magnetic and electric forces in a wave in order to obtain the direction of propagation, it is usual to assume that the electric force in a wave travelling over salt water is vertical. This seems to be justified for waves which have travelled without refraction or reflection. But where long distances are concerned the possibility that a portion of the wave has suffered successive refractions and is not travelling parallel to the earth's surface at the moment of striking the direction finder is not to be ignored. Such conditions apart, the problem of direction-finding is reduced to that of finding the direction of the magnetic force.

Perhaps the most straightforward method of doing this makes use of the fact that the direction of the magnetic force at any point near a ship is a function of the direction of the force in the undisturbed field of the wave. The exact nature of this functional relation cannot be predicted from theory, for the reason that the boundary conditions which the waves have to satisfy are too complicated for analysis. But the relation can be obtained in the form of a graph by experiment. A search coil, which need not be greater than 3 ft. square, is mounted in a definite position in the ship so as to be capable of rotation round a vertical axis, and is connected to a suitable amplifier. A transmitting station, the true bearing of which can be obtained by visual sights, is directed to transmit a suitable signal, while the search coil is revolved until its plane is parallel to the magnetic force in the region where it is situated. Silence is then obtained in the telephones. The true direction of incidence of the wave is known, and the apparent direction is perpendicular to the plane of the search coil in the "silence" position. It is only necessary to repeat the experiment for waves incident in many different directions to enable one to deduce, on any subsequent occasion, the true direction from the apparent direction.

The operation of finding the amount of correction to be applied to a direction finder is referred to as "calibrating the set." The calibration of a direction finder after it has been installed is a most important operation and experience has indicated certain precautions which should be taken. To reduce the chance of any errors due to atmospheric effects the calibration should be performed at short ranges. At the same time one has to consider the effect of the inductive field of the transmitter. At short ranges this modifies the nature of the total field considerably. It may sometimes make it impossible to take a bearing at all. A distance of four wave-lengths is regarded as the least distance at which it is safe to calibrate a ship. It is found that the shape of the transmitting aerial is of some importance. At short ranges more sharply defined readings can be obtained from a station which is symmetrical about a vertical feeder, such as an umbrella aerial, than from one which possesses a large roof on one side only of the feeder and is therefore unsymmetrical about the vertical.

To eliminate altogether the use of the compass, which itself is liable to error, and also a knowledge of the ship's position, which is sometimes difficult to obtain, the transmitting station should be clearly visible, so that its bearing relative to the centre line of the ship may be taken at any instant by pelorus or equivalent device. It is important to see that all movable metal structures near the coil are housed in their normal positions. It is particularly important that the positions of all stays which can form part of closed conducting loops should be known. The occasional opening and closing of conducting loops is a prolific source of erratic bearings. It is good practice to insulate all stays near the direction finder.

Lastly it is necessary to remember that all wireless direction finders give bearings, in the first place, relative to the ship's head. As it is sometimes difficult to keep the ship's head steady throughout the period (say 5 minutes) required for a series of readings, it is necessary to arrange that each visual observation, which gives the exact bearing of the transmitting station, is taken at the same instant as the wireless bearing. Direct buzzer communication between the wireless office and the bridge is the common practice in H.M. Navy. It is found well to let the wireless operator choose the instant for taking the bearing, as his operation is somewhat more delicate than that of taking a visual bearing.

### Deviations due to a Ship.

The number of degrees by which the true bearing differs from the apparent bearing depends, of course, on the position of the rotating coil. It is greatly influenced by the proximity of large metal structures such as funnels. For a 3 ft. frame coil situated between the two central funnels in one four-funnel ship the apparent bearing differed from the true bearing by as much as 32° for waves incident approximately on the bows or quarters. With the same coil situated on the quarter deck the maximum correction to be applied to the apparent bearing was 10°. A correction which varies from 0° to 32° is unsatisfactory for the reason that a slight error in the observed bearing involves a further error in the appropriate correction; and these errors will sometimes be additive.

Some means is required for reducing the magnitude of the deviation. The exact effect of a body of finite conductivity on an electromagnetic wave cannot be found theoretically. By assuming the conductivity infinite or by neglecting dielectric currents in comparison with conduction currents, solutions have been given for certain simple cases, notably for a long cylinder. The form of the solution usually differs according as we consider points near to the conducting body or at a considerable distance. In the latter case we are said to be dealing with the scattered wave. In practical direction-finding this hardly concerns us. It is the field in the immediate neighbourhood of the conductor which matters. This varies rapidly in direction from point to point, so that where the aerial system is large it is a question of line integrals of electric force, rather than of a uniform magnetic field of a certain strength threading a loop of a certain area.

It has been found, as a result of experiments in many types of ship, that the following method of regarding the action of the metal work of the ship leads to results which are supported by the facts. Every conductor on which an electric wave impinges has currents induced in it. Every filament of current so produced possesses a magnetic and an electric field, and sets in motion a secondary train of waves which spread out in all directions in space.

The magnetic and electric fields which act on the direction-finding system can be regarded as composed of:—

(*a*) The fields due to the main wave itself; and

(*b*) The secondary fields due to currents induced in neighbouring conductors by the main wave.

To find the resultant field at any point we have to add together, with due regard for direction and phase, all the fields which result from the innumerable filaments of current induced in every conductor in the ship. We have to consider further how these fields depend upon the direction in which the waves strike the ship, their variation with wave-length, and how they are modified by the tuning of other aerials in the ship. Given the form of the undisturbed field, to deduce an expression for the field at any point near the ship is beyond analysis. But as in the analogous case of the deviations of a magnetic compass, the general form of the result can be predicted from simple considerations.

Imagine a wave to be travelling parallel to the centre line of the ship. Consider the case, which is common in practice, where all structures and stays are symmetrical about the centre line. The induced currents which flow in the metal structures can be resolved into two components:—

(*a*) Those which flow in closed conducting loops.
(*b*) Those which involve capacity currents through the dielectric.

Except at short wave-lengths components of type (*a*) predominate in large metal structures such as funnels, while type (*b*) are relatively more important in masts, stays and aerials. Although the actual distribution of structures may be very complicated they can be replaced, so far as their effect in producing a secondary magnetic field at a point on the centre line is concerned, by a loop and a vertical aerial. The loop has its plane in the centre line of the ship; the aerial also lies on the centre line. The loop provides a component of the secondary magnetic field which varies with the direction of the incident wave, while the aerial gives a component which is independent of direction.

Similarly, when considering a wave incident athwartships, we can replace the deck structures by a loop and a vertical aerial. The aerial will be on the centre line and the plane of the loop athwartship. Thus there are altogether two loops and two aerials. Of the loops one lies fore and aft in the central plane of the ship and the other lies athwartship. The two aerials are both on the centre line and can therefore be replaced by a single aerial also on the centre line.

Although it is impossible to predict the sizes and positions of the equivalent loops and aerial, their main effects can be deduced. Let F be the fore and aft loop, B the athwartship loop and A the aerial. Let $\boldsymbol{H} \sin \omega t$ be the magnetic field of a wave incident in a direction $\theta$ to the centre line of the ship. The magnetic field in the athwartship direction at a point P on the centre line is made up of:—

$H \cos \theta \sin \omega t$ due to the main wave;
$fH \cos \theta \sin \omega t$ due to the loop F; and
$aH \cos \omega t$ due to the aerial A.

Here $f$, $b$ and $a$ are fractional coefficients depending on the dimensions of F, B and A and the position of the point P. The coefficient $a$ vanishes if the effects due to the innumerable antennæ currents mutually cancel at the point P.

It will be noted that the aerial is taken to be far from resonance. Thus while the currents which flow in the loops are opposite in phase to the electric force in the wave, the currents which flow in masts and stays are in quadrature.

The magnetic field in the fore and aft direction at P is made up of:—

$H \sin \theta \sin \omega t$ due to the main wave.
$-bH \sin \theta \sin \omega t$ due to the loop B.

The angle $\phi$ which the resultant field at P makes with the centre line is defined by the equation

$$\tan \phi = \frac{(1 + f) \cos \theta \sin \omega t + a \cos \omega t}{(1 - b) \sin \theta \sin \omega t}$$

It will be noticed:—

(1) That unless $a$ is negligibly small the field is not stationary in direction but rotates. The field is no longer linear and cannot therefore be said to have a direction, except instantaneously. Any method of direction-finding which depends upon finding the steady direction of the magnetic force ceases to be exact. Instead of getting complete silence for one position of the frame or search coil the most that can be obtained is a minimum of sound, whereas with a magnetic field which is truly linear the greater the amplification the more precise the position of silence. With a rotating field great amplification is no help; in fact, it is often easier to estimate the position of minimum sound by reducing the amplification until the signal is just inaudible at the minimum.

(2) When $a$ is very small, or vanishes, the apparent direction of the wave relative to the centre line of the ship is $\psi = \phi \pm 90°$. This is related to $\theta$ by the equation

$$\tan \psi = \frac{1 - b}{1 + f} \tan \theta$$

The deviation, i.e. $(\theta - \psi)$, is quadrantal; for

$$\tan (\theta - \psi) = \frac{(b + f) \tan \theta}{1 + \tan^2 \theta}$$
$$= \tfrac{1}{2}(b + f) \sin 2\theta \text{ (approx.)}$$

since $b$ and $f$ are small fractions.

Thus $\psi$ differs from $\theta$ by a small angle proportional to $\sin 2\theta$.

## RELATION BETWEEN WAVE-LENGTH AND DEVIATION.

The current which flows in a closed untuned loop depends upon:—

(*a*) the induced E.M.F., and
(*b*) the impedance of the loop.

(*a*) increases uniformly with frequency; so also does (*b*), provided the resistance of the loop is small. Thus, for waves of the same field strength the loop current is the same for all wave-lengths. The coefficients $f$ and $b$ are independent of wave-length, and therefore the quadrantal deviation is also independent of wave-length.

The current which flows in a vertical aerial increases with the frequency until resonance is reached, and then decreases. The secondary field of the aerial A therefore changes in magnitude with wave-length. The coefficient $a$ is not constant. Thus the deviations due to capacity currents vary with the wave-length. The existence of unbalanced capacity currents is the most serious difficulty in directional wireless in ships. All existing types of direction finder for use on a ship fail at some sufficiently short wave-length, depending on the conditions. A ship which is able to take bearings on waves of 150 m is exceptional. The theory of loop circuits in uniform magnetic fields ceases to be applicable at very high frequencies, and dielectric currents become sufficiently important to mask the simple effects which predominate when the wave is very long compared with the ship. Fortunately the effect of the presence of appreciable capacity currents is not so much to cause wrong bearings as to spoil the readings altogether, so that a bearing cannot be taken. Their presence can easily be recognized by the following characteristic effects, which are in accordance with the equations given above:—

(1) The zeros are poor, i.e. for every position of the search coil, whether within a goniometer or in the field of the wave itself, an E.M.F. is induced in it. A position of minimum sound, more or less difficult to locate, is all that can be obtained.

(2) The minima are most indefinite when the waves are incident athwartship, and for short wave-lengths.

(3) The derivations, as deduced from the positions of the minima, are not quadrantal. For the position of the search coil for minimum sound depends not only on the amplitudes of the fore and aft and athwartship components of the field, but also on their relative phase.

(4) The deviations vary with the wave-length.

### Effects of Neighbouring Aerials.

Similar effects are produced by the action of other aerials in the ship. Several aerials are commonly in use at the same time in a man-of-war. These aerials, according to their disposition and tuning, react on the direction finder and may completely falsify its readings. It is therefore necessary to find by experiment what the magnitude of their effect is.

The procedure adopted is as follows, and can be carried out with advantage in harbour, where the ship's head is fixed. A transmitting station is directed to transmit a signal at specified times, say on 2 000 m. Bearings are taken on the direction finder while the main aerial is tuned for reception, first on 500 m then 1 000 m and so on by steps up to 4 000 m. A record is kept of the wave-lengths (if any) at which (*a*) the zero becomes blurred, and (*b*) the zero (or minimum) shifts. The experiment is then repeated with the transmitting station on a different wave-length, and for any other aerials sufficiently near to the direction finder to be suspected of affecting the bearings. It is generally found that the zero becomes blurred before it shifts in position. For this reason it is unusual for an error of bearing to be due to the tuning of another aerial. With an experienced operator the quality of the zero is seen to suffer so noticeably that he knows that something is wrong. It is laid down for guidance in Admiralty Orders that whenever a zero is blurred and not sharply defined the bearing is to be regarded with suspicion and not used for navigation purposes. Whatever may be the cause, whether the waves, the apparatus, or the ship, the presence of a blurred zero is a sure indication that the bearing is unreliable.

In one ship which has been investigated there are four funnels and the directional wireless office is situated between the two foremost ones. For waves incident athwartship there is therefore great lack of symmetry. This soon shows itself by giving poor readings for short waves incident on either beam. At 2 000 m the effect is not noticeable, at 600 m it is pronounced, while at 300 m it is sufficient to spoil the readings altogether. When cruising parallel to a coast line this causes much inconvenience, for good bearings cannot be taken of nearby 600-m stations without altering the direction of the ship's head. In another ship, which possesses only one funnel, aerials were placed, for the purpose of experiment, immediately abaft the funnel. Here again it was found that the great lack of symmetry produced all the characteristic effects mentioned above. To a smaller degree the same thing has been observed in ships in which one funnel is taller than the other, but it is necessary to go down to 450 m in these ships before the quality of the readings varies noticeably with the direction of incidence.

### The Aerials.

To get rid of the *a* components two means are available. We may either find a position for the aerials so far removed from metal work that the amplitude of the secondary field is very small; or we may select a position for the aerials in which the metal work is disposed symmetrically around them. As an example of the first and less common method a four-funnel ship may be cited in which a special platform has been supported above the directional wireless office between the two central funnels. The platform serves two purposes. It carries a frame coil, and it supports the insulators for the Bellini-Tosi loops, which are erected so that they lie entirely above the level of the tops of the funnels and midway between the masts. It has been found that this arrangement is excellent from an electrical point of view. The quality of the zeros is uniformly good, even down to 200 m. By using sufficient amplification the readings are made so sharp that it requires no skill or experience to read them to $\frac{1}{2}$°. At the same time the quadrantal deviation has a maximum of 2°.

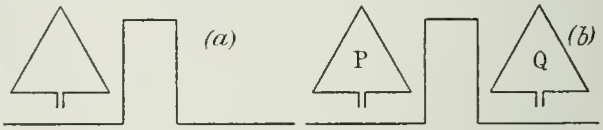


Fig. 1.

As a general rule in a man-of-war, and sometimes in other ships, it is impossible to put the aerials, whether of the rotating frame or the Bellini-Tosi type, in a position well clear of metal. Under these circumstances every effort has to be made to utilize the symmetry in the distribution of the metal which is often found in a ship. Otherwise the curve of deviations, even in the absence of rotating fields, becomes unsymmetrical and it is found impossible to provide suitable correctors. For this reason direction finders are nearly always located on the centre line.

Aircraft carriers are among the few ships which are unsymmetrical about the centre line, but in this class of ship it has been found possible to put the direction finder so far from the disturbing metal, which forms an island on one side of the flying-off deck, that its effect is small.

The Bellini-Tosi system has certain advantages in this respect. Take the case of the single funnel (Fig. 1). A loop placed as at (*a*) is unsatisfactory, but the arrangement shown at (*b*), in which two aerials are disposed symmetrically with respect to the funnel and connected in series, is free from objection. Thus by making the aerial system itself a composite one, the electrical centre of the whole may be in a position where no actual coil or aerial could be placed. Sometimes the structure the influence of which it is desired to eliminate permits of a system of coils being built into it. Four frames A, B, C and D may be used, all at 45° to the centre line and disposed symmetrically round the structure. Opposite frames A and C and also B and D are joined in parallel, and the whole is then equivalent to two perpendicular coils on the centre line and inclined at 45° to it. By connecting A and B and also C and D in parallel we have a system equivalent once more to two perpendicular coils on the centre line, one of which, however, is directed fore and aft and the other athwartships. This method of connection is sometimes an advantage, for it becomes possible to correct a quadrantal error by suitable adjustments inside the office.

### Laboratory Method of Examining Deviations.

It will be appreciated that to build a system of coils into the metal work of a ship is a costly matter. It is therefore very desirable to feel confident, in any particular case, that the results will be satisfactory. The difficulty is greatest for new types of ships, where the positions of the frames have to be decided in advance of construction, and full-scale experiments are out of the question. Some kind of laboratory method of investigating each case as it arose was felt to be needed. Fortunately a method of sufficient accuracy is available.

Consider a perfectly conducting body placed in a field of electromagnetic waves. At the junction of the conductor and the dielectric the tangential electromotive intensity and the tangential magnetic force are continuous. For a perfect conductor it follows that the magnetic force at points very near the obstacle is everywhere tangential, while the electric force is normal. This is true for waves of any frequency. At wireless frequencies it is very nearly true for an obstacle the conductivity of which is not perfect but is of the same order as that of common metals. The magnetic flux is unable to penetrate the obstacle, but is forced to slide round it.

Now consider a perfectly diamagnetic body placed in a steady magnetic field. Here again the magnetic flux cannot penetrate the body. Thus the boundary conditions in the two cases are identical, and, provided the obstacle considered is small compared with the wave-length, the distribution of the lines of magnetic force is very nearly the same in the two cases.

A perfectly diamagnetic substance is not known, but the same kind of equations which are satisfied by a magnetic field are true of the motion of an incompressible fluid. For instance, imagine a liquid flowing steadily through a tank. If a small model of a ship is introduced the lines of flow of the liquid are disturbed. The new positions which they take up when the steady state is reached are similar in every way to the lines of magnetic force in the case of a metal ship bathed in wireless waves, provided always that the waves are long compared with the ship. It becomes fairly easy to picture the effect on the waves of, say, a 12-inch gun. It is clear, too, that the magnetic field near a ship is very different from the field of a plane wave travelling without obstruction over a horizontal conductor. At most points the magnetic force is not horizontal nor is the electric force vertical. The elementary theory of a loop in a field of plane waves needs to be modified when we are considering a ship. It is a question of line integrals of electric force. To get a true zero on a Bellini-Tosi system the line integral of the electric force taken round one loop must have a resultant phase which coincides with that of the line integral of the electric force round the other loop. Hence the great need for symmetry.

By means of the lines of flow of a liquid some qualitative effects can be demonstrated, but it is found more convenient to get quantitative results in another way. Suppose we are considering the alternating magnetic force between two funnels, which in light cruisers are often of different section. Take a large sheet of zinc, say 8 ft. by 3 ft. by 0·02 in. Pass a steady current of 20 amperes through it and find a region near the centre of the sheet where the flow of current is uniform. Cut out a pattern to scale to represent a section through the two funnels. We have then two holes in the sheet into which the current cannot penetrate. The lines of flow of the steady electric current in the zinc sheet are the same as the lines of magnetic force in the wireless case. The analogy is exact only for very long funnels, but valuable approximate results have been obtained in this way. For example, it is easy to find at what distance from a funnel, or a number of funnels, the field is sufficiently uniform to put a Bellini-Tosi set. It is important to know this because the equality of the fields acting on opposite sides of the loops is necessary to get sharply defined readings. This is especially so at short wave-lengths where unequally distributed electrostatic forces within the goniometer spoil the readings. For a single funnel it is found that a safe distance is four funnel diameters.

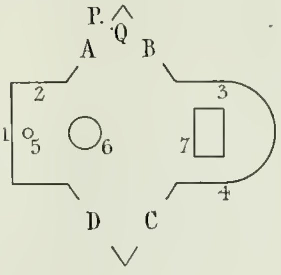


Fig. 2.

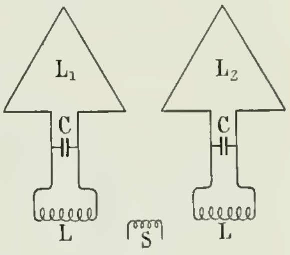


Fig. 3.

Another example is to find a suitable disposition of frame coils round a metal structure. Fig. 2 indicates how the zinc sheet was cut in one case. Slits 1, 2, 3 and 4 represent metal plating running round a platform. Holes 5, 6 and 7 represent masts and other metal work. Spaces A, B, C and D represent the positions of the frame coils, which are at 45° to the centre line. The current can stream through these spaces just as the magnetic flux in the wireless case streams through the frame coils. The pattern is cut so that the centre line is at 45° to the (undisturbed) line of current-flow in the sheet. Take the case where A and C are joined in parallel, and also B and D. We wish to know the ratio of the magnetic flux through A and C to the flux through B and D for waves incident at 45° to the centre line. Each space such as A is investigated as follows. Two points P and Q 2 mm apart are taken so that PQ is perpendicular to the frame. The potential difference between P and Q for a total current through the sheet of, say, 40 amperes is measured by the deflection of a galvanometer, thermo-electric E.M.F.'s being allowed for. The operation is repeated for a number point distributed along the space A. The sum of the deflections of the galvanometer is then a measure of the magnetic flux threading the frame coil. The other frames are treated in the same way. In one case the following figures were obtained :—

Deflections (mm).

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Coil A. | 37, | 23, | 11, | 6, | 4, | −2, | −9. | Total | 70 |
| Coil C. | 9, | 13, | 15, | 17, | 18, | 20, | 24. | Total | 116 |
| Coil B. | 130, | 154, | 182, | 210, | 219, | 228, | 241. | Total | 1 364 |
| Coil D. | 245, | 223, | 206, | 173, | 168, | 163, | 146. | Total | 1 324 |

The apparent direction of the wave relative to the frames BD is given by

$$\tan\theta = \frac{\Sigma A + \Sigma C}{\Sigma B + \Sigma D} = \frac{186}{2\,688}$$

whence $\theta = 4°$.

The deviation is therefore 4°. As the analogy is only strict for plates of metal and masts indefinitely tall this is likely to be an overestimate of the actual deviation.

The effect of a long conducting cylinder on an electromagnetic wave has been examined theoretically by Mr. S. Butterworth,* and I have used his results to verify that the zinc sheet gives reliable information. Take the direction of propagation as the axis of $x$, with the electric force parallel to $z$, which is also the axis of the cylinder. Along the $x$ axis the magnetic force, which is parallel to $y$, is greater than in the undisturbed field. It reaches its maximum value at the two points where the $x$ axis cuts the surface of the cylinder. Here it has double the normal value. Along the axis of $y$ the magnetic force is everywhere less than normal, and at the surface of the cylinder is zero. The rate of variation of the magnetic force in both cases is large near the surface of the cylinder. This indicates that it is necessary to be very careful of the exact positions of frames which are placed near to masses of metal. Similarly, where ordinary single-turn loops are used they must either be very rigid or else kept at some distance from such structures as funnels if small changes in their position are not going to matter.

To get good results by the method outlined above it is essential to have sheet metal of uniform thickness. It is advisable to examine the constancy of the potential gradient over the region where it is proposed to cut a pattern. Any small variations of thickness or conductivity can then be allowed for in the measurements which are made subsequently. The pattern itself should be small compared with the dimensions of the sheet. In every direction round the pattern it should be possible to find places where the current has become sensibly uniform once again, or the corrections for the finite size of the sheet become difficult.

### Methods of Correcting for Deviations.

To correct a quadrantal error it has been the custom for some time to place the aerials in the Bellini-Tosi system one fore and aft and the other athwartship, and to make the area of the fore and aft loop less than that of the athwartship loop. For the final adjustment it is usual to reduce the effect of the aerial which is receiving too strongly, by inserting inductance in its circuit where the loops are untuned, or resistance where the loops are tuned.

With untuned loops the insertion of loading inductance increases the impedance of the circuit by the same fraction at all frequencies. When the quadrantal deviation is eliminated for one wave-length it is automatically eliminated for other sufficiently long wave-lengths, i.e. long compared with the length of the ship.

With tuned loops the correction by means of resistance is dependent on the frequency. The ratio of the added resistance to the total resistance of the circuit varies with frequency, and a quadrantal corrector needs to be adjusted for each different wave-length.

For some purposes it is a disadvantage to have loops with different electrical constants. One disadvantage is that a limit is set to the length of cable which can be run from the aerials to the office without causing errors. This is dealt with later. Another disadvantage is that the time constants of the two aerial circuits are very unlikely to be the same. This is immaterial where continuous waves are used, but for spark waves the effect is to blur the zero and flatten the readings. The explanation of this lies in the fact that with spark signals a steady state of oscillation is never reached. Every second, 500 or so damped oscillations are set up in each of the two aerial circuits, and these oscillations cannot keep step with each other unless the circuits have identical time constants. The currents in the field coils get out of phase with each other and blurred zeros result.

If an E.M.F. $E \sin pt$ is applied to a circuit the inductance, capacity and resistance of which are $L$, $C$ and $R$ respectively, the expression for the current produced contains terms of the form :—

$$e^{-(R/2L)t}(A \cos qt + B \sin qt)$$

where

$$q = \sqrt{\left(\frac{1}{LC} - \frac{R^2}{4L^2}\right)}$$

The frequency $q/2\pi$ and the damping both depend on the time constant of the circuit. Thus if two circuits of different time constants are acted on by E.M.F.'s of the same form, the resulting currents contain oscillatory terms of different frequency and damping. With spark signals the damped oscillations appear every time a spark passes. The blurring effect operates continuously. With undamped waves the transient terms appear only at the instant of pressing the key and soon after have so small an amplitude as to be inappreciable.

---

* *Philosophical Transactions*, 1922, vol. 222, p. 57.

By having a special goniometer it is possible to use aerials of identical shape and size, and therefore of identical time constants, and still correct for a quadrantal error without altering the aerial circuits. Such a goniometer has been used recently in one ship. It has two fixed coils A and B with no mutual induction, each coil lying entirely outside the other. Each coil is constructed after the manner of a Helmholtz galvanometer, so as to give the most uniform possible field. The search coil is a composite system consisting of two coils $S_1$, $S_2$ which rotate together, one within the field of each fixed winding, $S_1$ within A and $S_2$ within B. $S_1$ and $S_2$ are joined in series and arranged so that when the axes of $S_1$ and A are parallel the axes of $S_2$ and B are perpendicular, and vice versa.

The behaviour of this system is precisely the same as that of an ordinary goniometer, but it has the advantage that $S_1$ and $S_2$ can be adjusted independently. For instance, if coil A is joined to the fore and aft aerial and this is found to be too strong for the athwartship aerial, a few turns may be removed from the coil $S_1$, or it may be shunted by an adjustable inductance, which can conveniently be placed external to the coil system and have no coupling with it.

Under these circumstances several desirable results are achieved. First, the two aerials can be rigged identical in shape and size and then left untouched—a great convenience in ship work. Secondly, the time constants of the two aerials are equal, which makes them suitable for heavily damped spark signals. Thirdly, it is easy to use tuned aerials, for the tuning and resistance of the aerials are identical. Lastly, the correction for quadrantal deviation is true for all frequencies with both tuned and untuned aerials.

### The Direction-Finding Office.

It is often difficult or impossible in a ship to provide an office near to the position most suitable for the aerials. One of the advantages of the Bellini-Tosi system in a man-of-war is that the office can be placed below armour and connected to the aerials by cables. In order not to introduce any error the two pairs of wires which come from the aerials have to satisfy two conditions: first, that no mutual induction exists between them, and secondly, that the total E.M.F. in each pair, due to the direct action of the wave, vanishes. This is not difficult to achieve; but it is necessary to have regard to two additional factors. The first is the capacity per foot of each pair of wires, and the second is the power factor of the cable. With the circuit employed in a Bellini-Tosi system the capacity C in the cable is shunted across the goniometer field coils L (Fig. 3). This means that only a portion of the current circulating round the loops is available to affect the search coil S. The higher the frequency the more serious the shunting capacity of the cable becomes.

Under ordinary circumstances and for untuned aerials the most suitable goniometer to use is one in which the field coils have an inductance equal to that of the aerials. It may be noted, however, that the shunting effects of cable capacity are reduced by reducing the inductance of the goniometer. Thus where it is desired to use long cables it becomes worth while to use a goniometer the field coils of which have an inductance less than that of the aerials. Goniometers having field-coil inductances of 10 $\mu$H are used in this way in ships, and it is found that the cable capacity can then amount to 0·0015 $\mu$F before any trouble is experienced on waves of 450 m and above, even though the two loops differ considerably in inductance. However, when the loops have different inductance the effect of putting equal capacities across the goniometer windings is to make it impossible to correct quadrantal errors automatically for all frequencies. If $E$ is the ratio of the E.M.F.'s in the two loops $L_1$, $L_2$, and $C$ the ratio of the currents in the field coils L, $E/C$ varies with the frequency.

In fact $$\frac{E}{C} = \frac{L_1 + L(1 - \omega^2 L_1 C)}{L_2 + L(1 - \omega^2 L_2 C)} \text{ (approximately)}$$

Waves incident in the same direction, but of different frequency, have the same value for $E$ but different values for $C$ and therefore different apparent directions. The deviation is a function of the frequency, and much simplicity is lost. By using the special goniometer described above, the aerials can be made identical and there is no limit to the length of cable which may be used, except loss of signal strength.

The power factor of the cable is most important with tuned loops where the resistance losses in the circuit fix the amplitude of the current. A twin-core cable in which the cores are separated by 6 mm of pure rubber insulation has been found to have a low power factor for wireless frequencies as compared with ordinary braided rubber-insulated cables.

In one respect less trouble is experienced in a man-of-war than is usual at shore stations, viz. in screening the instruments inside the office. It is essential in all direction finders that the amplifier should receive no energy except through the aerial. If appreciable E.M.F.'s are induced in the receiving apparatus by the direct action of the waves or by re-radiation from the aerials, the bearings are spoiled. Of the total voltage applied between filament and grid of the first valve of the amplifier, not more than about 1 per cent should be due to such direct action, if the bearings are to be accurate to ½°. At shore stations, where it is not common to have screened receiving huts, this involves elaborate screening of the amplifier and other instruments. In a man-of-war the steel plating of the office constitutes an effective Faraday cage and further screening is unnecessary.

The fact that all direction finders give bearings relative to the centre line of the ship adds a slight complication to ship work. To get true bearings it is necessary to allow for the direction of the ship's head at the moment of taking the reading of the direction finder. For this reason a compass repeater is fitted in directional wireless offices. Immediately after taking the wireless bearing the reading of the compass is recorded. It is then a simple calculation to deduce the true bearing. But the necessity for calculation involves the possibility of mistake and loss of time. Where observations are being made on hostile aircraft, speed of working is important. A direct-reading instrument is therefore a great advantage and incidentally avoids errors of calculation. The goniometer now in use in several ships of the Royal Navy provides a direct-reading scale and great ease of manipulation. The scale of the instrument is made to follow the movement of the ship's head by connecting it to the transmitter system of the gyro-compass. The reading opposite a fixed mark is always the same as the reading of the master compass. The reading opposite the pointer of the instrument when the " zero " is obtained is the true geographical bearing of the transmitting station or ship.

## DISCUSSION BEFORE THE WIRELESS SECTION, 6 JUNE, 1923.

**Captain C. E. Kennedy-Purvis, R.N.** : Before the discussion opens I should like to make a few remarks for the benefit of those who may not be conversant with Naval requirements. Direction-finding in the Navy has two chief functions ; the first is the location of enemy signals, etc., and the second for navigational purposes, as in the Mercantile Marine. The first function is the more important and necessitates a large range of wave-length adjustments. The troubles which are inherent as regards fitting and working are several. The first, as may be seen from some of the figures, is extreme congestion on the upper deck, guns and turrets (which have a habit of moving at the critical time), bridges, masts, funnels, searchlight platforms, control towers, etc. These often make it very difficult to find positions which are suitable for the purpose. In certain ships it has been found to be absolutely impossible to find room for the Bellini-Tosi type of aerial, and other arrangements have had to be made. Another trouble is the congestion below decks, which renders it difficult to find space for the instruments within a reasonable distance of the aerials. Another difficulty touched upon by the author is the multiplicity of other aerials—receiving and transmitting—nearly all in action at once and necessarily in the neighbourhood of the direction-finding aerials. Gun-blast and its effect on aerials of every type in the immediate vicinity is a further source of worry.

**Mr. N. Lea** : It is, I think, to be regretted that the author has not given us a little more of his experience in regard to the relative advantages of small loops and large loops. The idea of using a small loop is introduced in the early part of the paper in connection with the calibration of the ship, but it seems to have been abandoned quite early. The author points out that when a large loop is used it is necessary to introduce the idea of integration, in order to form some kind of mental picture as to what is happening in the circuit. On page 1053 he says : " To get a true zero on a Bellini-Tosi system the line integral of the electric force taken round one loop must have a resultant phase which coincides with that of the line integral of the electric force round the other loop. Hence the great need for symmetry." Further on, he says : " For example, it is easy to find at what distance from a funnel, or a number of funnels, the field is sufficiently uniform to put a Bellini-Tosi set. It is important to know this because the equality of the fields acting on opposite sides of the loops is necessary to get sharply defined readings." There are, it seems to me, a number of main considerations which should control the size of the loops. First, the size should be such that the integrated field passing through the loop is upset as little as possible by semi-movable objects. Looking at it from rather a detached point of view, it would seem to me that the chances of finding what I may call a quiet spot are greater with a small loop than with a large loop. Secondly, the loop size should be such that it is possible to make it susceptible to the magnetic wave component only, and so avoid the rotating field mentioned by the author. Small loops can be screened to a large extent by a metallic mesh having open ends in the form of a comb, but this is not, of course, possible in large loops. Lastly, the loop should be free from deformation at all times. Small loops can be quite rigid and unaffected by wind, the ship rolling in a sea-way, and rigging stresses when handling cargo. Then the small loop is many times simpler from a circuit point of view, and there is much less chance of the constants being upset and therefore errors being introduced. In the most up-to-date installations having large loops I think it is usually the practice to abolish tuning, owing to phase difficulties, and the large loop would therefore appear to have no appreciable advantage either from the point of view of the amplification required or from that of the range obtained. On page 1055 the author refers to the use of large, tuned loops, but in view of a great deal of experience this seems to me to be somewhat risky. The small loop may, of course, be rotated, and it is easy to apply the important principles which have been introduced by Dr. Robinson, and I think that is undoubtedly of valuable assistance from the operator's point of view, since it is easier to judge an equality. That is, I realize, to some extent a debatable point. At any rate, there is no doubt that the scheme whereby bearings are taken on an equality of signals is less upset by the poorness of minimum than the straightforward Bellini-Tosi method. The installation must, for general purposes at any rate, be simple and should not require the attention of the whole of one's technical staff in adjusting the circuits, etc. On page 1049, in referring to the relation between the true direction of the wave and the apparent direction when in the neighbourhood of metal objects, the author says : " The exact nature of this functional relation cannot be predicted from theory, for the reason that the boundary conditions which the waves have to satisfy are too complicated for analysis. But the relation can be obtained in the form of a graph by experiment. A search coil, which need not be greater than 3 ft. square, is mounted in a definite position in the ship so as to be capable of rotation round a vertical axis, and is connected to a suitable amplifier." It seems rather a pity that every possible step should not be taken to employ that simple arrangement by finding a suitable place for the receiving apparatus in the ship. If we have two large loops it is physically impossible to adjust the two loops to have exactly the same constants, and, as all practical engineers will realize, it is perhaps even more difficult to keep those constants steady. With regard to the question of the automatic compensation for the quadrantal errors, I realize that for naval purposes, where speed is absolutely essential, this has some points in its favour, but simply from the point of view of accuracy I think it is a mistake; the quadrantal error varies from time to time from various causes, and if the operator has a dial from which he can read the bearing directly he is liable to overlook these errors. The automatic compensation introduced by the author into his circuits would appear to legislate only for the sine law of deviation, and it is not absolutely certain that the error is always strictly quadrantal. The author's method of investigating a design of a direction-finding installation by means of a zinc plate is very interesting, and I should like to know whether he has tried the introduction of a partial conductivity in the slits in order to imitate the effect which would be produced by a metal rail.

**Dr. R. L. Smith-Rose:** The difficulties in operating a direction-finding station on shore are by no means few, but in this case one has the advantage of making observations relative to some fairly permanent base; whereas in the case of a ship one is dealing with an object which very frequently has a three-dimensional motion, in addition to the acute local disturbances due to the ship itself. I feel rather strongly upon the question of the ultimate necessity for the direction-finding observations to be carried out on the ship instead of on the shore. I think that it is by no means easy at the present time to determine with any accuracy by ordinary navigational methods the position of a ship which is not in sight of land or other fixed points; yet the reputation of wireless direction-finding at the present date is not so good as to cause the average navigating officer to repeat a calculation of his position when the latter does not agree with that given by a group of direction-finding stations on shore. With the wireless observations actually carried out on the ship under his personal supervision, he would be much more likely to appreciate the accuracy to which the readings could be taken and repeated, and ultimately to gain the confidence in the art which is so necessary to its successful application in this direction. The two essential points which increase the difficulties of carrying out direction-finding measurements on a ship compared with those on shore are (1), the determination of the direction of the ship's head, and (2), the effect of the local metal work. The first point is necessary because all wireless observations are taken relative to the ship itself, and the direction of the ship must be obtained from the compass. All the errors involved in obtaining this direction are included in the wireless direction-finding observations. The magnetic compass is by no means an ideal instrument with which to obtain the direction of the ship's head, and to appreciate this fact one has only to realize that the error of an uncorrected compass on a steel ship is usually greater than the largest quadrantal deviation observed with a wireless direction finder. Even when the correcting spheres are attached to the ship's compass one is inclined to place too much faith in its readings. The calibration of the magnetic compass is usually carried out at four cardinal points only, and, when using two or more "standard" compasses on board a ship, positions can often be found at which the readings of the respective compasses differ by as much as 3 or 4 degrees. Even with the compass reading correctly in its steady state on a ship, and particularly on small ships which are rolling or yawing badly, the needle may attain such an amplitude in its swing as to cause a lag of several degrees between its reading and the instantaneous direction of the ship's head. No such lag is present on the direction finder, so that this may be a source of error under these conditions. It is far preferable also that the compass should be in the wireless office under the direct observation of the direction-finder operator, for, however precise may be the means of buzzer communication to a remotely placed compass observer, there is an added personal error and possible time-lag in the latter's observation, and this should be eliminated. The gyro-compass gives possible freedom from most of the errors mentioned above, and has the advantage that a repeater dial may be placed beside the wireless instruments, or, as stated in the paper, may be used actually to rotate the goniometer scale, so that the readings of the latter are automatically corrected for the direction of the ship's head. In any case, since our present knowledge of the direction finder on board ship indicates the possibility of the reduction of most of the errors involved, the person responsible for installing a wireless direction finder on a ship is justified in demanding the best compass available for use in connection with his work. The effect of the local metal work on a ship is indeed a very serious matter, but the author's analysis of this is very helpful in showing the manner in which the quadrantal deviation can be reduced to reasonable proportions. If, as stated in the paper, the deviation can be reduced to a maximum value of 2°, the ship direction finder is greatly improving its position; for it is seldom that a land direction-finding station has an error of less than 2° in every direction. The author's laboratory method of examining deviations must be a very efficient substitute for the carrying out of costly full-scale experiments on difficult types of ships. On page 1053 the author remarks that "the elementary theory of a loop in a field of plane waves needs to be modified when we are considering a ship." I am not quite clear in what respect this theory has to be modified, for surely this elementary theory may be considered as a line integral of electric force around the loop or as a surface integral of magnetic force over the area of the loop and perpendicular to its plane. Calculation in the correct manner by either method should give the same value for the E.M.F. induced in the loop, and also the conditions for symmetry of the two loops. Referring now to the leads from the aerial loops to the direction finder, would it not be better to employ paper-insulated cables instead of solid rubber-insulated cables, and so reduce the power factor of those leads? Although it is not usually done, it is a comparatively easy matter to screen sufficiently the whole of the receiving room of a shore station in order to avoid direct pick-up of signals. One experimental station screened in this manner, using a receiver comprising two tuned, coupled circuits and a 9-valve amplifier, gives complete absence of any audible signal from a $1\frac{1}{2}$ kW ship's transmitter only a few miles away, while observations of bearings accurate to within 1–2 degrees are easily obtained on similar transmitters at distances exceeding 100 miles with the aerials connected up. This screening of the entire station from direct pick-up, however, does not render unnecessary the screening or adequate spacing of the individual instruments inside the office in order to avoid errors due to mutual inductance between the different circuits involved in the receiver. I have had some rather concentrated experience recently on the operation of the Bellini-Tosi system, the Robinson system, and also the single-frame system as used on land. I have not used these systems on board ship, but the actual results would appear to be similar. Neglecting any question of cost and difficulty of erection, I think that the Bellini-Tosi system is rather quicker to operate than either of the others. It is much easier to swing a small goniometer search coil than to swing a frame coil, even if the latter is only 3 or 4 ft. in magnitude. In the case of a shore station the capital cost of erection of a station is possibly negligible compared with the cost of maintaining and running the station, but in the case of a ship, where the direction finder may be used on relatively few occasions, the factor of cost may be rather an important one, and in that case I think that the frame coil has an advantage over the Bellini-Tosi system, and I certainly think that on all commercial ships a position could be found in which the quadrantal errors need not be larger than is neccessary to secure good working and the accuracy required for navigational purposes. The Bellini-Tosi system gives one the impression of being a more solid engineering job, while the mass of the moving part is much smaller, but it has the disadvantages that it has more loopholes for errors, and that it requires very skilled and experienced engineers for its installation and calibration. In regard to the relative advantages of the Robinson system and the single-coil system, I think that for the purpose for which it was designed the Robinson system certainly scores on the question of precision. One also gains the impression that a much more accurate reading is obtained on a steady scale than with either the scale or pointer moving as in swing readings. On the other hand, the chief disadvantage in the Robinson system is that it does not tell the operator what is the nature of the minimum, and, as the author points out, the condition of things at the minimum often affords a good indication to the operator as to the reliability of the bearing. It is very difficult to detect night errors in the Robinson system if one does not know what the true bearing should be. The paper shows in several instances that the errors on a ship direction finder increase rapidly as the wave-length is decreased. In a similar manner most of the errors and difficulties experienced at shore direction-finding stations are increased as the wave-length is reduced. I should therefore like to raise the question as to whether in the author's opinion, and possibly that of other members, 450 m is the most desirable wave-length to be allocated to direction-finding in this country, or whether a higher wave-length would not be preferable. It is, of course, desired to keep within the range of adjustment of the majority of the low-power ship and shore transmitting sets. On 600 m the normal interference is usually too bad to make accurate direction-finding possible over any appreciable distance, especially in the neighbourhood of land and ports when it is probably most needed. Again, on the 450 m wave the interference is at times so bad as to make accurate observation very difficult, so that a longer wave, such as 750 m—or possibly 800 m, to come into line with American direction-finding stations—is to be preferred, and this, if standardized, would entail little modification of the majority of ship's transmitters. Care would, of course, have to be taken that the allocation of such a wave for direction-finding purposes, particularly if beacon stations are to be set up on an extended scale, did not itself make interference a serious disadvantage on this wave-length.

**Mr. L. Bainbridge-Bell:** The author describes the electrical method of correcting quadrantal error. This method appears to have no advantage over the use of a table of corrections in cargo ships, in which the draught varies between wide limits. In the curve shown on the lantern slide, a change of draught from 26 ft. to 14 ft. changed the maximum quadrantal error from $9\frac{1}{2}$ degrees to 5 degrees. Using the electrical method of correction (such as resistances or inductances in the loops) in this and similar cases, it would be necessary to re-calibrate a ship after every change of draught, whereas in using a table or preferably a chart (like the one shown) it is possible to interpolate between the extreme values given and to get a suitable correction. To my mind the above considerations also nullify the advantage of incorporating a gyro-compass dial in the direction finder. The quadrantal error is a function of the bearing of the distant station from the ship's head, and therefore the bearing from the ship's head would have to be observed, in addition to the bearing measured from true North, in order to determine the quadrantal correction. According to the author, the variation from point to point of the field strength is likely to make bearings unreliable owing to "blurrings" of zeros. When taking bearings by the Robinson method, using coils about 3 ft. square enclosed in an electrostatic screen, i.e. a screen with no closed loops in it, no trouble was experienced in the case of a ship where the coils were only two funnel diameters from the funnel, although the funnels were very high. The next slide shows the position of the coils in one of the Union Castle ships, which has very tall funnels. It will be seen that the coil is very close to the funnels. The maximum quadrantal error obtained in this case was 18 degrees, but there was no difficulty in taking the bearings and a perfectly regular curve of quadrantal error was obtained, and the quality of the zeros (observed by using one coil only) did not suffer at all as a result of the position of the coils. On page 1050 the author describes the method of calibrating the direction-finding set by using a land station. It has been noticed that if the aerial on land is situated on steeply sloping ground, completely erroneous results are obtained. Results have been obtained which make the apparent position of the land station in some cases $\frac{1}{4}$ mile away from its real position. Therefore, in using that method, care has to be taken that the configuration of the land is suitable for the calibration. In discussing his special goniometer with two coils, each completely outside the other, the author states that the correction for quadrantal deviation is true for all frequencies. Is it not a fact that the quadrantal deviation, apart from the system of direction-finding used, is a function of the ratio of the size of the ship to the length of the wave?

**Major H. P. T. Lefroy:** The problem dealt with by the author is very much the same as that which has to be solved in all-metal aircraft; not quite the same, because in his case the metal is almost entirely underneath and around his coils, whereas in the latter case it is almost entirely above and below; but the complexity of stays, etc., is the same in both cases. The common aircraft direction-finding method of using a rotating coil will have to be abandoned in metal fuselages, as the screening is too great, so that fixed-wing coils must be used; but, if fixed wing-coils only are used, the course of the aeroplane must be changed to find the direction of a transmitting station. This is a disadvantage, to overcome which it seems best to use, in conjunction with the wing-coils, the rotary search-coil of the Bellini-Tosi system. Has the author observed any practical difference between the errors due to steel and any other metal, for instance duralumin? Again, is there much practical difference between the errors due to various thicknesses of metal? If so, what is the critical thickness? Lastly, is there a minimum critical distance from a mass of metal within which it is very undesirable to put any wire of a loop aerial?

**Major B. Binyon:** As some remarks have been made on the advantages of shore directional stations, I think it is worthy of note that at least one instance has occurred of a ship having gone aground on account of its inability to obtain bearings in fog from a coastal direction-finding station, and such stations will always have the disadvantage that in time of fog every ship in the vicinity may require bearings and considerable delay must arise. However, we are aiming to-day at the prevention of accidents as far as possible, and for this purpose ships must be fitted with direction finders in order that they can obtain bearings upon one another and so reduce the risk of collision. Further, the captain of a vessel is the sole person responsible for the safe navigation of his ship and he is likely to place much more reliance on bearings which have been taken by his own navigating officers, and which he can compare with his dead-reckoning, than on any bearings given him from coastal stations taken by observers whom he does not know and who will not accept any responsibility should such bearings prove inaccurate. There are, of course, many other arguments in favour of the use of direction finders aboard ship in lieu of coastal stations, more particularly the reduction of interference and the fact that as many bearings and checks may be obtained as is desired. Also, I think that the importance of this method of navigation is borne out by the fact that the Navy have seen fit to entrust the author and others with an investigation of this problem in so thorough a manner.

**Admiral Sir H. B. Jackson:** A good many questions have been asked in regard to the accuracy of direction finders. I agree that it is better for a captain of a ship to take his own bearings. The paper shows the enormous difficulty which the Navy has had in getting accurate direction-finding on board their ships with their various shapes of funnels and masts, etc., but ships in the Mercantile Marine are much more of a standard pattern except in minor details, and I think that if the matter were brought before the Naval architects, shipowners and builders of merchant ships, they would take an interest in this matter and would be willing to design a special platform for these direction finders in the fore part of the ship. This is the more important end when approaching land; we should then be freer from error, as Major Binyon has described. If a Naval architect knows that he has to put something in a certain place he can do it without much extra cost or trouble during the building of the ship. I hope that Naval architects will take the matter up carefully in order to assist the Mercantile Marine in fitting direction finders on board ship.

**Mr. E. H. Shaughnessy:** First of all there is the question, referred to in the discussion, of the most suitable wave-length. There is no definite wave-length fixed for this country for direction-finding at the present moment. A wave-length of 450 m appears to be used, but ships' directions are given by the Post Office Niton Station on 600 m wave-length, and at the International Technical Conference in Paris two years ago it was decided that wave-lengths of 450 m, 600 m or 800 m should be used for direction-finding. Probably in due time, with the experience which we are now obtaining, the best wave-length will be found, and it may be that if the proposal to use 600 m as a calling wave and 800 m as a working wave for ships is adopted, 800 m will not be possible for direction-finding, but 600 m may be. Another question referred to in the discussion was as to whether the direction finder should be on the ship or on the shore. It must be remembered that the cost of running a direction-finding station on shore is fairly high, because a staff is required, apart from the capital cost, and unless there is quite a large amount of traffic it is not a very paying proposition. If, however, the apparatus is fitted on board ship, and if we can get results such as are shown in the paper to be obtainable, then it simply means that the ship has only to pay for a direction-finding apparatus, whatever type may be used, and the ordinary operator can take its position without having to keep any special staff. From a general point of view it would appear to be a cheaper method to fit the direction finder on the ship. It would also, as has already been pointed out, give the captain of the ship the opportunity of deciding definitely whether he thought his results were sufficiently reliable for him to act upon, or not; he would be quite independent of some other organization in giving him results.

**Mr. C. E. Horton** (*in reply*): Mr. Lea questions whether there is ever any advantage in using large loops instead of small frames. It is a vexed question and everything depends upon the particular conditions which obtain on the ship under consideration. I should, however, like to point out that a rotating frame implies an office not far from it, whereas with untuned loops it is easy to arrange, by using suitable cables, to have the office several hundred feet away. I cannot agree with Mr. Lea that a small frame is any protection against the evils of a rotating magnetic field. As regards the use of partial conductivity in the slits in the zinc sheet, I do not think such an arrangement would provide a true analogy.

Dr. Smith-Rose observes that the E.M.F. induced in a loop circuit is correctly given by elementary theory and can be calculated in more than one way. But on a ship the distributed capacity to other metal in the vicinity of the wires comprising the loops, involves the existence of important capacity currents, ignored in the elementary theory but very important at short wave-lengths. The merits of paper-insulated cables are considerable but I have not found such cables to possess a power factor at high frequencies less than that of cables with pure rubber insulation. I agree with Dr. Smith-Rose that the technical difficulties of direction-finding would be less on 800 m than on 450 m, as at present.

Mr. Bainbridge-Bell questions the advantages of automatic correctors for quadrantal errors. One advantage is precisely that they make it possible to incorporate a gyro-compass dial in the direction finder. It is just as easy to alter the corrector for each change of draught as it is to apply a fresh correction by calculation, and no more calibrating is required in one case than in the other. Approximate equality in the fields acting on the two sides of a loop is easier to obtain with a small frame than with an extended Bellini-Tosi aerial. The frame can therefore be placed nearer to a disturbing mass of metal than can a large loop, before the zeros begin to suffer in quality. Were this the only consideration the small frame would always be preferred.

In reply to Major Lefroy, I have not found any difference in the errors due to steel and other common metals, nor any effect due to different thicknesses of metal as commonly used in constructional work. The thickness of metal would probably need to be excessively small before it became important. The critical distance from a mass of metal within which it is undesirable to put a loop aerial depends on the dimensions of the metal and of the loop. With a single rotating frame the criterion is that it should be far enough away from the metal to lie in a region where the magnetic field is sensibly uniform, or symmetrical about the axis of the frame.

# THE CALCULATION OF AIR-SPACE FLUX.[*]

By Professor W. CRAMP, D.Sc., Member, and NORA I. CALDERWOOD, M.A., B.Sc.

(*Paper first received 27th April, and in final form 11th July, 1923.*)

## SUMMARY.

With the increase of alternating-current apparatus and the spread of wireless telegraphy, the calculation of air-space flux, whether electromagnetic or electrostatic, becomes daily of greater importance. At present the old formulæ of Forbes are used, supplemented by certain cases developed by Maxwell, Thomson, Carter and others. This paper extends the number of these cases, and develops therefrom close approximations in forms of immediate use to the designer. The results thus obtained are compared with the older formulæ, by means of examples. The following is a list of the chief cases considered :—

I. The flux between equal equipotential surfaces in parallel planes.
II. The flux between equal parallel equipotential surfaces in the same plane.
III. Variation in Case I produced by surfaces like those in Case II.
IV. The effect of the outer surfaces of two equal equipotential surfaces in parallel planes.
V. The flux issuing from a taper pole-shoe.
VI. The flux distribution in a stepped recess.
VII. Calculation of capacities by means of the same theorems.

## INTRODUCTION.

With the development of alternating-current apparatus, the correct calculation of magnetic and electrostatic flux in an air-space has become of ever-increasing importance. In the case of direct-current apparatus, an error of 20 per cent in a leakage factor can often be covered by a factor of safety in design, and rough methods suffice ; whereas such an error in the estimation of an impedance or a capacity might be attended by very inconvenient results. In any case, the correct prediction of the performance of a piece of apparatus must ever be the desideratum of the designer, so that exact theorems put into such a form as to be readily applicable to practical cases are sure to be welcome.

In a region of uniform permeability or permittivity whose boundaries are equipotential surfaces, the distribution of the stored energy may be represented by the division of the space into a number of cells each containing the same quantity of energy. In two dimensions each cell is bounded by two lines having a specified potential difference between them, and two perpendicular to these and proportional to them enclosing a specified quantity factor usually termed "flux."

The distribution of these cells is always difficult to determine and depends upon the principle that they will so arrange themselves as to make the potential energy of the system a minimum. It cannot yet be deduced theoretically except in the simpler cases, so that in this problem at present the electrical engineer is awaiting the progress of the pure mathematician. Several cases are represented in the beautiful plates in Maxwell's treatise and to these a few have been added by the 'Recent Researches" of Sir J. J. Thomson ; while, to meet the requirements of practice, graphical methods have been suggested by Lord Rayleigh, by Richardson[*] and by Lehmann.[†]

On account of the difficulties in exact computation, engineers until 1900 worked almost entirely from approximations derived from the three lemmas of Forbes.[‡] In that year, however, and subsequently, more accurate solutions of three very useful cases were given by Carter, covering the effective area of an air-gap under a rectangular pole, the effect of slots upon the area of a gap, and the leakage flux at the mouth of a slot. Upon such data, extended by useful approximate integrations, designers have hitherto been dependent, and it is the purpose of the present paper to extend the work of Carter, by putting the results of a few more cases into a form that is readily applicable.

In order to render our work more general, we propose, as far as possible, to divide it into sections suggested by the Forbes cases and directly comparable thereto. As we proceed, the limitations to this plan will become obvious and departures from it inevitable. It is, however, the system to which the designer is already accustomed, and therefore for him will present the least difficulty.

Theoretically the flux crossing an air-gap must be treated as a whole for each individual case. But the plan of dividing up the charged surfaces into parts, according to the planes in which they lie, and treating each part independently, has the convenience of enabling us to derive approximate formulæ applicable to a wide range of examples ; and further, it gives results immediately comparable with existing methods. Strictly, however, it is not legitimate, since it involves the suspension of an integration at a point arbitrarily selected, and consequently leads occasionally to obvious discrepancies when limiting cases of converging approximations are compared. This disadvantage, however, does not in our opinion weigh substantially against the practical utility secured, provided that its existence is clearly recognized.

---

[*] The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on Papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[*] *Philosophical Magazine*, 1908, Series 6, vol. 15, p. 237.

[†] *Electrotechnische Zeitschrift*, 1909, vol. 30, p. 995.

[‡] See W. CRAMP : "Continuous Current Machine Design," pp. 226 and 227 [Harper Bros.]. Useful integrations are also given on pp. 227–229, and Carter's results on pp. 40, 41 and 47. See also *Electrical World*, 1901, vol. 38, p. 884 ; *Journal I.E.E.*, 1900, vol. 29, p. 929 ; and *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, pt. 1, p. 1067.

### I. The Flux between Equal Equipotential Surfaces in Parallel Planes (Fig. 1).

According to Forbes's first lemma, the flux produced by each ampere-turn exciting the gap of length $2h$ is $(4\pi/10) \times (A/2h)$, where $A$ is the area of one of the opposing faces. This assumes that all the flux lines are uniformly spaced, of equal length and normal to the two surfaces. Also it assumes that the regions marked B in the figure do not affect the distribution of the flux. Both assumptions are entirely unwarranted, and the expression is very far from being correct for any cases except those in which $A/2h$ is very large. If, however, the region B be neglected, the flux distribution is similar to that appertaining to the lines of electrostatic flux between the plates of a parallel plate condenser, which may be deduced from Maxwell's "Electricity and Magnetism."[*] If for this ideal case we take a section through Fig. 1 (*a*) normal to the gap surfaces, the latter would be represented by the two parallel lines of Fig. 1 (*b*). If these be supposed to be in the plane of $x$, $y$, with the origin on the median line as shown, Maxwell's equation applied to the magnetic problem becomes :—

$$x + iy = \frac{h}{M}\phi + i\frac{h}{M}\psi - \frac{h}{\pi}\left(1 + \epsilon^{-(\phi+i\psi)\pi/M}\right) \quad . \quad (1)$$

where $M$ is the magnetic potential difference across the semi-gap $h$, $\phi$ is the flux and $\psi$ the potential function. Thus

$$x+iy=\frac{h}{M}\phi+i\frac{h}{M}\psi-\frac{h}{\pi}-\frac{h}{\pi}\epsilon^{-(\pi/M)\phi}\left(\cos\frac{\pi}{M}\psi-i\sin\frac{\pi}{M}\psi\right)$$

And if for the upper surface $\psi = M$,

$$x + iy = \frac{h}{M}\phi + ih - \frac{h}{\pi} + \frac{h}{\pi}\epsilon^{-(\pi/M)\phi} \quad . \quad . \quad (2)$$

Now between the surfaces $\epsilon^{-(\pi/M)\phi}$ rapidly diminishes, so that

$$\phi = \frac{M}{h}\left(x + \frac{h}{\pi}\right), \text{ nearly}$$

Or the flux per ampere-turn per cm depth,[†] referred to the semi-gap, is :—

$$F' = \frac{4\pi}{10h}\left(x + \frac{h}{\pi}\right) \quad . \quad . \quad . \quad . \quad (3)$$

From this reasoning it is clear that the flux fringe increases the effective pole-face by the fraction $h/\pi$, and that if the linear dimensions of the area $A$ be $x$ and $b$, so long as $h$ is smaller than $x$ and $b$ the allowance for the increased permeance due to the bulging of the lines in the centre of the gap is obtained by increasing both $x$ and $b$ by $h/\pi$, and this correction must be made wherever such bulging can take place. Thus for Fig. 1, instead of Forbes's formula

$$F = (4\pi/10) \times (A/2h) \quad . \quad . \quad . \quad . \quad (4)$$

we get
$$F = \frac{2\pi}{10h}\left\{\left(x + \frac{2h}{\pi}\right)\left(b + \frac{2h}{\pi}\right)\right\} \quad . \quad . \quad (5)$$

where $F$ is the flux corresponding to each ampere-turn exciting the total air-space.

Cases in which Equation (5) is of use do occur in practice, especially in connection with eddy-current brakes, electric meters and the like, where, to obtain a uniform and reasonable density over a long gap, pole-pieces of the form shown in Fig. 2 are used. Assume in such a case that $x = 5$ and $b = 8$, so that $A = 40$, and suppose that $2h = 1$, then the Forbes expression gives $F = 50{\cdot}24$, and Equation (5) gives 56, so that the error by Equation (4) is more than 10 per cent, and gets greater as $2h$ increases in comparison with $x$ or $y$.

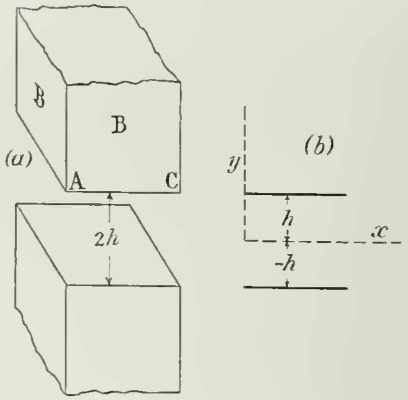


Fig. 1.—Forbes's first lemma.

In such instances Equation (5) is sufficiently accurate for the surfaces considered, but takes no account of the backs of the pole-pieces marked C in Fig. 2, which will be dealt with later. If, however, surfaces rise perpendicular to A, as shown at B in Fig. 1, the whole distribution in the gap is thereby modified, and the correction when the vertical surfaces are very long compared with the gap $h$, is obtained at once from Carter's first case. We show later, however (see p. 1065), that under these circumstances, for the usual proportions existing between pole face and air-gap :—

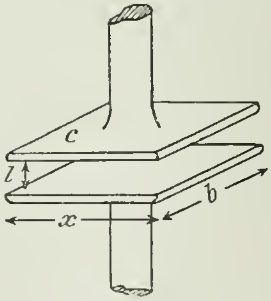


Fig. 2.—Eddy brake pole-shoes.

$$F' = \frac{2\pi}{10h}\left\{x + \frac{2h}{\pi}(1 - \log 2)\right\}$$
$$= \frac{2\pi}{10h}\left(x + \frac{0{\cdot}6138h}{\pi}\right) \quad . \quad . \quad . \quad . \quad (6)$$

so that the presence of the vertical surfaces reduces the correction for the flux between the surfaces in the ratio of 1 : 0·6138.

---

[*] 2nd edition, arts. 195 and 202. Also J. J. Thomson : "Recent Researches in Electricity and Magnetism," art. 235.

[†] Throughout this paper "depth" is always measured perpendicular to the plane of $x$, $y$.

These formulæ are based on the assumption that $h$ is smaller than $x$ or $b$, and themselves become inaccurate when either $x/h$ or $b/h$ approaches unity. This, however, seldom occurs in practice, and when it does the value of $F'$ can always be obtained by calculation from the original equations.

### II. Two Parallel, Equal, Equipotential Surfaces in the Same Plane.

Two approximate solutions of this case were given by Forbes. The first (Fig. 3) is intended to meet those problems in which the gap between the surfaces is relatively short, while the other (Fig. 4) contemplates cases in which $d$ is larger than $r$. In such instances, more than in Case I, the form and disposition of the adjacent surfaces affect the permeance to be calculated, but this is neglected in the Forbes lemma.

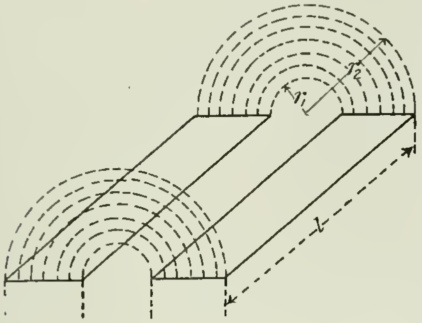


Fig. 3.—Forbes's second lemma, first case.

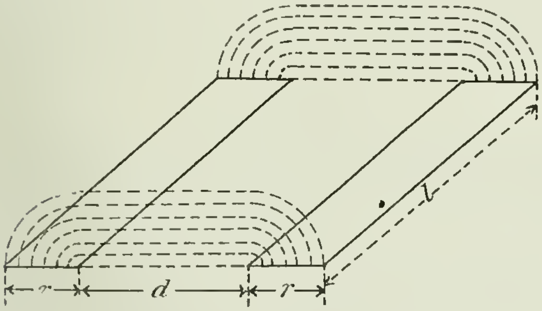


Fig. 4.—Forbes's second lemma, second case.

The form of the lines of flux assumed by Forbes is indicated in the figures, and his formulæ are :—

For Fig. 3, $F = 0{\cdot}4l \times \log \dfrac{r_2}{r_1}$

and for Fig. 4, $F = 0{\cdot}4l \times \log \dfrac{\pi r + d}{d}$. . . . (7)

Now it is well known that the distribution of the flux is not in the least like that supposed in Fig. 4, even when the adjacent surfaces are neglected. Fig. 3 is, indeed, much nearer the truth, and becomes substantially accurate when $r_1$ is very small as compared with $r_2$. It is also well known that if $z = (x + iy)$ represent a plane normal to both of the surfaces considered and to their longer edges, so that the trace of the plane by the surfaces is the $x$ axis, then the elliptic transformation

$$x + iy = b \times sn(\psi + i\phi) \quad . \quad . \quad . \quad (8)$$

gives the equipotential and flux lines in the $z$ plane, $\psi$ being the potential and $\phi$ the flux function. The value of $b$, moreover, is such that if the origin be chosen midway between the inner edges of the surfaces, the gap $d$ in Fig. 4 is $2b$ and the length $r$ is $b(1 - k)/k$, where $k$ is the modulus of the elliptic functions.*

This is a perfectly general result whatever be the ratios of $d$ and $r$, and it thus covers both the cases of Forbes. The diagram of the resulting equipotential and flux lines is well worth comparing with those of Figs. 3 and 4, and has, so far as we are aware, never been drawn out before. It is shown in Fig. 5, in which AB and CD are the traces of the surfaces along the $x$ axis, and O is the origin. The labour involved in drawing this diagram is considerable, for while with the aid of Legendre's tables individual points can be calculated, the points corresponding to definite constant values of $\psi$ and $\phi$ can only be obtained by plotting curves of the points calculated and interpolating from them. The method of arriving at the lines of the diagram is outlined in Appendix III.

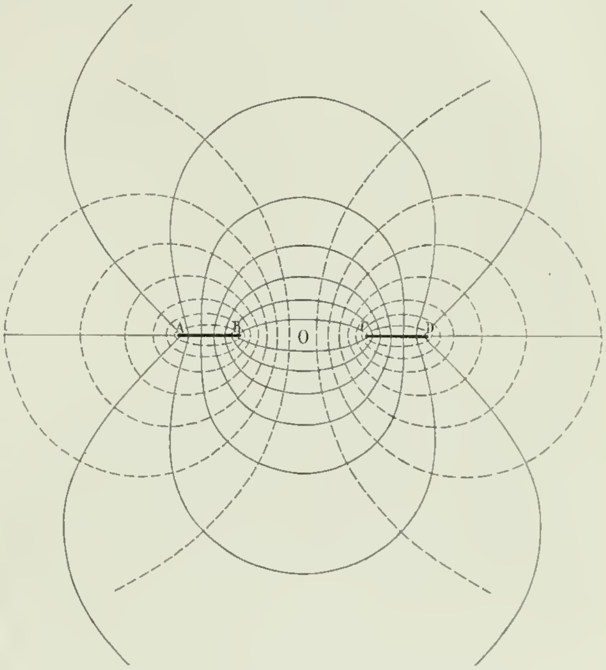


Fig. 5.—Flux and equipotential lines of two surfaces in one plane.

From the above transformation it follows that $F' = K'/(2K) \times 4\pi/10$, where $F'$ is the flux per ampere-turn per cm of depth, and where $4K$ and $2iK'$ are the real and imaginary periods of the elliptic functions. From this equation in turn the values shown in the

* An elementary statement on the elliptic functions is given in Appendix II. For a more extended discussion of this transformation the reader is referred to J. J. Thomson, "Recent Researches in Electricity and Magnetism," p. 236 par. 245. For a lucid account of conformal transformation and for a clear meaning of the potential and flux functions the reader is referred to the excellent article by F. W. Carter in the *Electrical World* and *Engineer* of Nov. 30, 1901

top curve of Fig. 6 have been calculated in a form useful to the designer, plotted against the values of $m$ as abscissæ, where $m$ is the ratio $(d + 2r)/d$.

For the same ratios and on the same sheet the corresponding values of the Forbes equation are shown in the bottom curve. On comparing the two, it will at once be seen how great is the error of the older approximation in those cases, common enough in practice, where $m$ is small; and even in the commonest cases the error may amount to 100 per cent. The new curve compares strictly with the conditions considered by Forbes, but, as it also neglects the effect of adjacent surfaces, it cannot be sufficiently accurate except in a few instances. We will therefore consider the modifications introduced by some special forms.

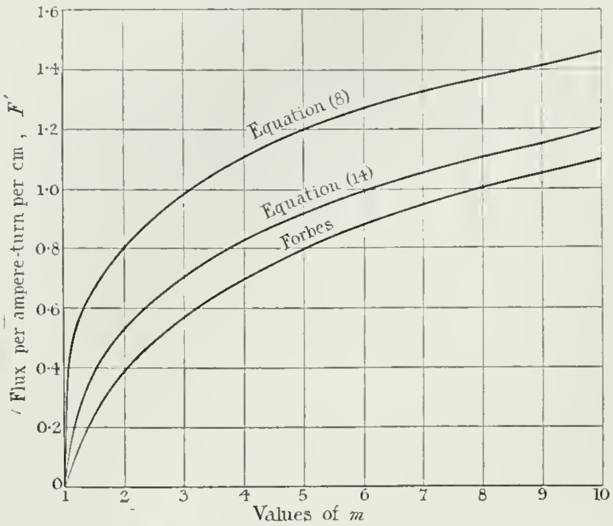


FIG. 6.—Values of specific flux from co-planar parallel surfaces.

One of the commonest cases is illustrated in Fig. 7.

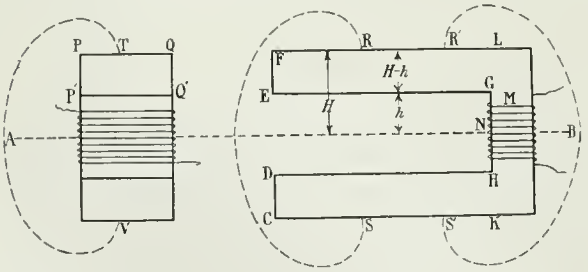


FIG. 7.—Typical magnet.

Here the parallel surfaces in the same plane are the ends, EF and CD, of the iron magnet. As the figure is symmetrical about the surface represented by the trace AB, we may calculate the flux issuing from either limb and this surface, regarded as being produced by half the ampere-turns of the coil M. Further, the distribution of the flux is such that if GN is small compared with EG, a very close approximation is obtained by regarding EG as semi-infinite, and the region bounded by ANGEFL may be represented in the $z$ plane by Fig. 8. This boundary we transform by the Schwarz-Christoffel method * into the real axis of a new region called the $t$ plane, choosing for the purpose the values of $t$ as shown in Fig. 8. We thus obtain :—

$$\frac{dz}{dt} = C\frac{\sqrt{t}\sqrt{(t-a)}}{t+1} \quad . \quad . \quad . \quad . \quad (9)$$

where $z = x + iy$ and $C$ is a constant.

This expression may be integrated as shown in Appendix I, and we then obtain :—

$$z=C\left\{\sqrt{t}\sqrt{(t-a)}+\left(1+\frac{a}{2}\right)\log\frac{2t-a-2\sqrt{t}\sqrt{(t-a)}}{a}\right.$$
$$\left.+\sqrt{(1+a)}\log\frac{\sqrt{(1+a)t}+\sqrt{t}\sqrt{(t-a)}}{\sqrt{(1+a)t}-\sqrt{t}\sqrt{(t-a)}}\right\}+K \quad (10)$$

where $K$ is the constant of integration, which is seen to be zero if the origin of co-ordinates in the $z$ plane is taken at $t = a$. It then follows that as $t$ passes through $-1$, the value of $y$ changes from $-H$ to $-H + h$, and from $t = 0$ to $t = a$ the change in $y$ is from $-H + h$ to zero. $C$ must therefore be determined so that as $t$ passes through $-1$, $y$ decreases by $h$. On substituting in the expression for $z$ first the value $t = -1 - e$ (where $e$ is a very small positive quantity) and then the value $t = (-1 + e)$ and subtracting the second result from the first, we find the change as $t$ passes through $-1$, and thus arrive at the result :—

$$C\sqrt{(1+a)} \times \pi = h$$

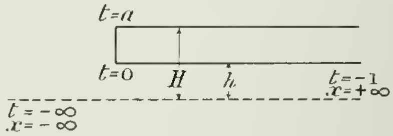


FIG. 8.—Boundary conditions for Fig. 7.

When $C$ has thus been determined a difficulty arises with Equation (10) owing to the ambiguity of signs in the terms involving square roots. No direct rule is available for settling this matter, and we were obliged to reach a solution by substituting various values for $t$. We thus found that to represent Fig. 8 correctly after cancelling all $i$'s, the plus sign must be taken for all arithmetical roots. Further, the imaginary term to be added in the case of the first logarithm is $-i\pi$, while for the second logarithm it is $+i\pi$. Then when $t = 0$, $y = -H + h$, and so :—

$$z=C\left\{(1+\tfrac{1}{2}a)(-i\pi)+\sqrt{(1+a)}\times(+i\pi)=i(-H+h)\right\}$$

Thus $\qquad H = C\pi(1 + \tfrac{1}{2}a)$

and, since $\qquad h = C\pi\sqrt{(1 + a)}$

$$H/h = (1 + \tfrac{1}{2}a)/\sqrt{(1 + a)} = m \text{ (suppose)} \quad . \quad (11)$$

Solving for $a$ we find :—

$$a = 2\left\{m^2 - 1 \pm m\sqrt{(m^2 - 1)}\right\} \quad . \quad . \quad (12)$$

The + sign must be selected, for $a$ must always be +, and as $m$ is always greater than 1 and positive, the first

---

* For an account of this method and works dealing with conformal transformation, see Appendix IV.

term is positive and the second greater than the first. Thus $a = 2\left\{m^2 - 1 + m\sqrt{(m^2 - 1)}\right\}$, and, when $m$ is very large, $a = 4m^2$.

In the plane of $\phi + i\psi$ the diagram is simply two parallel lines as shown in Fig. 9, the magnetic potential difference being that due to half the ampere-turns of Fig. 7 (say $M'$). Then :—

$$\frac{d(\phi + i\psi)}{dt} = B(t + 1)^{-1} \text{ where } B \text{ is a constant ;}$$

and
$$\phi + i\psi = B\left\{\log (t + 1) - i\pi\right\} \quad . \quad . \quad (13)$$

where the constant has been chosen so as to make $\psi = 0$ from $t = -\infty$ to $t = -1$. Along the lower surface $\phi$ must be negative, and as $t$ passes through $-1$, $\psi$ changes from 0 to $0{\cdot}4\pi M'$, so that $B = -0{\cdot}4M'$, and $\phi + i\psi = -0{\cdot}4\left\{\log (t + 1) - i\pi\right\}M'$. Then the flux per ampere-turn per cm depth along the surfaces CD and EF is :—

$$0{\cdot}4 \log (a+1) = 0{\cdot}4 \log\left\{2m^2 - 1 + 2m\sqrt{(m^2 - 1)}\right\} \quad (14)$$

This function has been plotted against values of $m$ in Fig. 6 and gives the intermediate curve in that figure. It is much nearer to the Forbes approximation, but still for values of $m$ less than 2 the error in the latter is very large, and amounts to about 100 per cent when $m = 1{\cdot}3$.

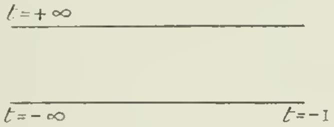


Fig. 9.—Potential conditions for Fig. 7.

## III. Variation in Case I produced by the Surfaces of Case II.

We have already remarked upon the change in the value of the flux in cases like Fig. 1 produced by the surfaces B. In Fig. 7 the surfaces indicated by EG and DH should fall under Case 1, but the absolute value of the depth EF, as well as the presence of the surface FL, will modify the correction already introduced in Equation (3), which was derived on the assumption that EF was very small compared with ED. Now in Equation (10), when $a$ is large compared with 1 and $t$ is nearly $-1$ :—

$$x + iy = \frac{h}{\pi\sqrt{a}}\left\{\sqrt{t}\sqrt{-a} + \frac{a}{2}\log\frac{-a - 2\sqrt{t}\sqrt{-a}}{a} + \sqrt{a} \times \log\frac{\sqrt{(1 + a)t} + \sqrt{t}\sqrt{(t - a)}}{\sqrt{(1 + a)t} - \sqrt{t}\sqrt{(t - a)}}\right\}$$

Then on rationalizing the last term and adhering to the convention of signs already established, we get :—

$$x + iy = \frac{h}{\pi\sqrt{a}}\left[-\sqrt{a} + \frac{a}{2}\log\frac{-a + 2\sqrt{a}}{a} + \sqrt{a} \times \log\frac{\left\{\sqrt{a}(-1) - \sqrt{a}\right\}^2}{(1 + a)t^2 - t(t - a)}\right]$$

so that

$$x = \frac{h}{\pi\sqrt{a}}\left\{-\sqrt{a} + \frac{a}{2}\log\left(1 - \frac{2}{\sqrt{a}}\right) + \sqrt{a} \times \log\frac{4}{t(t+1)}\right\}$$
$$= \frac{h}{\pi}\left\{-1 + \frac{\sqrt{a}}{2}\log\left(1 - \frac{2}{\sqrt{a}}\right) + 2\log 2 - \log (t+1)\right\}$$

Expanding the second term we have :—

$$\frac{\sqrt{a}}{2}\log\left(1 - \frac{2}{\sqrt{a}}\right) = \frac{\sqrt{a}}{2}\left\{\frac{-2}{\sqrt{a}} - \frac{4}{2a} - \frac{8}{3a\sqrt{a}} - \dots\right\}$$
$$= -1 - \frac{1}{\sqrt{a}} - \dots$$
$$= -1 \text{ (when } a \text{ is very large)}$$

so that
$$\frac{\pi x}{h} = -2 + 2\log 2 - \log (t + 1)$$

And substituting from Equation (13), the flux per ampere-turn of the complete coil, $M$, is : —

$$F' = \frac{-2\pi}{10h}\left\{x + \frac{2h}{\pi}(1 - \log 2)\right\} \quad . \quad . \quad (15)$$

From these expressions it is seen that when the thickness CD or EF is small the same approximation is possible as in Section I, viz. the increase of $x$ by $h/\pi$. But when the thickness is not negligible the value of $F'$ is decreased as the thickness increases until, when CD and EF become infinite (so that $a$ in Fig. 8 is infinite) the value $h/\pi$ is decreased by $0{\cdot}386\ h/\pi$. Thus the limits of the approximate correction for the fringing lie between $0{\cdot}318h$ for a very thin pole-face, and $0{\cdot}195h$ for a very thick one. Obviously, any exact case can be worked out from the equations given, where this is desirable, but in most cases judgment in the selection of a suitable coefficient lying between the above will be near enough. An example is given later, but we may here point out that the value $F = 56$ worked out for Fig. 2 becomes $F = 52{\cdot}3$ in a case like Fig. 1, so that the effect of the thickness is of some importance.

## IV. The Effect of the Outer Surfaces of Two Equal Equipotential Surfaces in Parallel Planes.

An instance of this occurs in the surfaces marked C in Fig. 2, and again in the surfaces indicated by FL and CK in Fig. 7. The only difference in these two instances is the thickness (as at EF in Fig. 7) which separates the interior from the exterior surfaces. Where this is very thin the case of Fig. 7 degenerates into the equation of Maxwell's article 202, but it may be remarked that it then seldom accords with anything likely to occur in practice. It is, however, useful as a limiting case to derive from Maxwell's equation the value of the flux issuing from the back of a thin pole-shoe.

Now from Equation (2) we have :—

$$\epsilon^{-(\pi/M)\phi} = \left(x - \frac{h}{M}\phi + \frac{h}{\pi}\right)\frac{\pi}{h}$$

and along the surfaces we are now considering $-(\pi/M)\phi$ is positive, and therefore the left-hand term above is increasing. Thus

$$F' = \frac{4\pi}{10h}\log\left(x + \frac{h}{\pi} - \frac{h}{M}\phi\right)$$

So that when $x$ is large compared with $h$, and calculating now upon the total ampere-turns impressed upon the gap of length $2h$, we have :—

$$F' = 0 \cdot 2 \log\left\{\frac{\pi x}{h} + 1 + \log\left(\frac{\pi x}{h} + 1\right)\right\} \quad . \quad (16)$$

to a first approximation. When, as frequently happens, $x/h$ is large, even this may be simplified to $F' = 0 \cdot 2 \log(\pi x/h)$, which means that the flux lines are semi-circles with radii varying from $h/\pi$ to $x$, and that the equipotentials are equally-spaced radial lines. Comparing the error introduced by this last approximation with Equation (16), we find that when $x/h$ is 10 the difference is about 3·2 per cent, and when $x/h$ is 100 it becomes quite negligible. For values of $x/h$ less than 10, Equation (16) is preferable, and when $x/h$ is less than 4 the full equation should be used.

Having thus established the approximate value for the flux issuing from the back of an infinitely thin shoe, we may consider the case when the shoe has a sensible thickness, i.e. when EF is a sensible proportion of the semi-gap $h$ in Fig. 7. Now in Equation (9), if $t$ is large compared with 1 we have :—

$$\frac{dz}{dt} = C\frac{\sqrt{t}\sqrt{t}\left\{1 - \frac{a}{t}\right\}^{\frac{1}{2}}}{t}$$

$$= C\left\{1 - \frac{1}{2} \times \frac{a}{t}\right\} \text{ (approx.)}$$

Integrating and determining the constant so that when $t = a$, $x = 0$, we find :—

$$x = C\left\{t - \frac{a}{2}\log t - a + \frac{a}{2}\log a\right\} \quad . \quad (17)$$

and $C$ has the value $h/\pi \sqrt{(1 + a)}$, as in Equation (10). The accuracy of this simple expression is very remarkable. For instance, in a practical example where $h = 5$, $H = 15$ and $x = 20$, the value of $t$ obtained from (17) and substituted in (13) gave $F' = 0 \cdot 27$, while the similar value obtained from Equations (10) and (13) was 0·28. In order to render the application as simple as possible in practice, Fig. 10 is appended. This gives the value of $F'$ for the back of a pole-shoe of sensible thickness plotted against $x/h$ for various values of $m$, where as before $m = H/h$.

Before proceeding with any further cases we will work an example to indicate the application of the foregoing analysis. For this purpose we select Fig. 7 with the following dimensions in cm : EG = 40, ED = 10, EF = 10, PQ = 12. The flux issuing from the surface FL and re-entering CK is in four parts, viz. for half the length there is a component indicated by RS, with a corresponding portion R′S′. And for each half of the width there is a component indicated by TV. Then $2h = 10$, $H = 15$, $H/h = m = 3$.

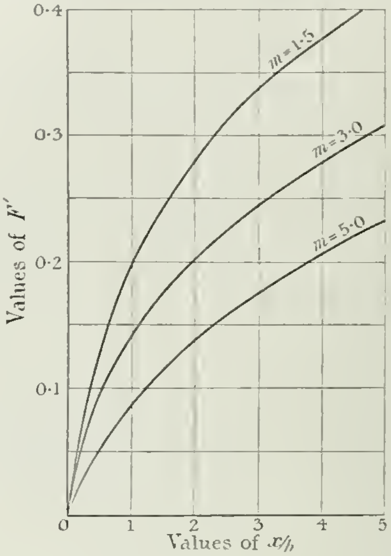


FIG. 10.—Specific flux from the back of parallel pole-shoes.

| Surfaces in diagram | Flux ($F'$) per amp.-turn per cm of depth | Derived from | Depth from diagram | Flux per amp.-turn | Flux per amp.-turn; Forbes's lemmas |
|---|---|---|---|---|---|
| EF | 0·705 | Fig. 6 (Eqn. 14) | 12 | 8·46 | 6·8 |
| PP′ | 0·705 | Fig. 6 (Eqn. 14) | 40 | 28·2 | 22·7 |
| QQ′ | 0·705 | Fig. 6 (Eqn. 14) | 40 | 28·2 | 22·7 |
| EG or P′Q′ | — | Equations 3 and 15 | — | 72 | 61 |
| Flux R′S′ | 0·28 | Fig. 10 ($x/h = 4$) | 12 | 3·4 | Neglected |
| Flux RS | 0·28 | Fig. 10 | 12 | 3·4 | Neglected |
| Flux TV | 0·155 | Fig. 10 ($x/h = 1 \cdot 2$) | 40 | 6·2 | Neglected |
| Flux TV | 0·155 | Fig. 10 | 40 | 6·2 | Neglected |
| | | | | 156·06 | 113·2 |

The error by the Forbes formulæ is thus seen to be 40 per cent. It is further of interest to compare the values of the fluxes EF and PP′ with those obtained from the top curve of Fig. 6. We find that the results are :—

| | Top curve | Middle curve |
|---|---|---|
| Flux EF . . . . | 11·76 | 8·46 |
| Flux PP′ . . . . | 39·2 | 28·2 |

The chief sources of error in the above calculation are the fluxes from the sharp corners and the omission of any allowance for the yoke—the latter case is one of a large class in which the surface potential is not constant and to which later we hope to return.*

## V. THE FLUX ISSUING FROM A TAPER POLE-SHOE.

In the cases discussed so far the polar surfaces have been parallel. In practice, however, they are far more often inclined to one another and have rounded edges. The case of a tapered shoe with a sharp corner † can be dealt with by a Schwarz-Christoffel transformation, but the rounded edge is not amenable to that treatment. A slight extension of Equation (1), however, enables us to solve this case for certain curvatures of edge.

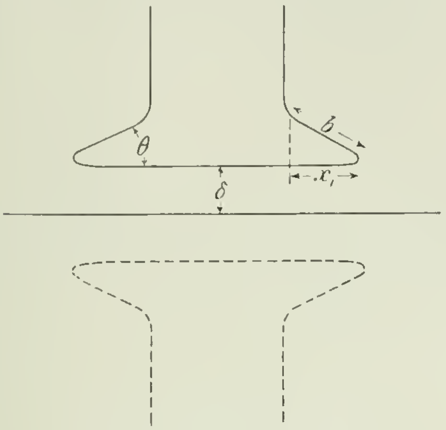


FIG. 11.—Taper pole-shoes.

For suppose $\psi = aM$, where $a$ is nearly unity. Then $\sin \pi\psi/M = \sin\pi(1-a) = \pi(1-a)$ (approx.).

Then

$$x + iy = \frac{h}{M}\phi + iah - \frac{h}{\pi} + \frac{h}{\pi}\epsilon^{-(\pi/M)\phi} + ih(1-a)\epsilon^{-(\pi/M)\phi}$$

whence

$$y = ah + h(1-a)\left\{\frac{\pi x}{h} + 1 + \log\left(\frac{\pi x}{h} + 1\right)\right\} \text{ (approx.)}$$

$$= h + h(1-a)\left\{\frac{\pi x}{h} + \log\left(\frac{\pi x}{h} + 1\right)\right\}$$

The second portion of this expression is the value of $y$ above the shoe surface, since the height of the latter is $h$; and $y = h$ when $x = 0$.

Again, putting $y = h$ and $\psi = aM$ in Equation (1) we get:—

$$x + ih = \frac{h}{M}\phi + iah - \frac{h}{\pi} - \frac{h}{\pi}\epsilon^{-(\pi/M)\phi}(\cos a\pi - i\sin a\pi)$$

$$1 = a + \frac{1}{\pi}\epsilon^{-(\pi/M)\phi} \times \sin a\pi$$

or

$$= a + (1-a)\epsilon^{-(\pi/M)\phi} \text{ (approx.)}$$

so that $\phi = 0$

and $x = \dfrac{-h}{\pi}(1 + \cos a\pi) = 0$, very nearly

Given, therefore, a pole-piece whose angle is, say, $\theta$ and air-gap $\delta$, with a magnetic potential difference $Mg$ across the gap (see Fig. 11) the flux from the pole-face and the sloping surface is obtained as follows:—

$$\pi(1-a) = \tan\theta\,; \quad h = \delta/a\,; \quad M = Mg/a$$

Projected length of pole-tip $= x_1$ (Fig. 11). Half pole-arc $= x$.

$$\phi = \frac{M}{h}\left(x + \frac{h}{\pi}\right) \text{ per cm depth for half the pole-face}$$

$$= \frac{M}{h}\left(2x + \frac{2h}{\pi}\right) \text{ per cm depth for the whole pole-face}$$

$$= \frac{Mg}{ah}\left(2x + \frac{2h}{\pi}\right) = \frac{Mg}{\delta}\left(\text{pole-arc} + \frac{2\delta}{a\pi}\right)$$

$$F' = \frac{4\pi}{10\delta}\left(\text{pole-arc} + \frac{2\delta}{a\pi}\right) \text{ under the shoe}$$

And in the case of the sloping back of the shoe:—

$$x_1 = \text{projected length of slope} = b\cos\theta$$

$$\text{Then} \quad \phi = \frac{M}{\pi}\log\left(\frac{\pi x_1}{h} + 1\right) \text{ per cm depth (approx.)}$$

$$= \frac{Mg}{a\pi}\log\left(\frac{a\pi b\cos\theta}{\delta} + 1\right)$$

$$F' = \frac{0\cdot4}{a}\log\left(\frac{\pi ab\cos\theta}{\delta} + 1\right)$$

$$= \frac{0\cdot92}{a}\log_{10}\left(\frac{\pi ab\cos\theta}{\delta} + 1\right)$$

Where a second pole-face exists, as shown dotted in Fig. 11, the air-gap being $2\delta$, and the ampere-turns refer to the whole gap, the value of $F'$ in each of the above expressions is halved.

The thickness of the shoe at the tip is in all cases $h(1-a)$ and its form is approximately that shown in Fig. 11. The formulæ presuppose that $x$ and $x_1$ are considerably greater than $\delta$, which of course is almost invariably the case.

As an example, suppose a pole-shoe having an arc of 20 cm, an air-gap $\delta = 0\cdot5$ cm, an angle $\theta = 30°$, and a length $b = 4$ cm. Also, let the ampere-turns acting across the gap be 3 000, and the depth of the face be 20 cm. Then $\tan\theta = 0\cdot58 = \pi(1-a)$; so that $a = 0\cdot814$. Then the flux issuing from the underside of the pole-face is:—

$$3\,000 \times \frac{4\pi}{10 \times 0\cdot05}\left(20 + \frac{2 \times 0\cdot5}{\pi \times 0\cdot814}\right) \times 20$$
$$= 3\,074 \times 10^3 \text{ maxwells}$$

And the flux issuing from the sloping backs of the shoe is:—

$$3\,000\,\frac{0\cdot92}{0\cdot814}\log_{10}\left(\frac{\pi \times 0\cdot814 \times 4 \times 0\cdot866}{0\cdot5} + 1\right)$$
$$\times 2 \times 20 = 172\cdot4 \times 10^3 \text{ maxwells}$$

---

* For an analysis of some cases in which the surface potential is not constant, the reader is referred to the paper by Mr. B. Hague on page 1072.

† *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, p. 1130.

That is, the latter is about 5·6 per cent of the former and by no means negligble. Also the fringing correction under the face (apart from the backs of the shoe) is seen to account for 74 000 maxwells.

### VI. FLUX DISTRIBUTION IN A STEPPED RECESS.*

This case was suggested to one of the authors as the result of a consideration of the slot used by Professor Miles Walker in the machine described † by him before the Institution some time ago, and a solution was at that time given for one part of the figure.

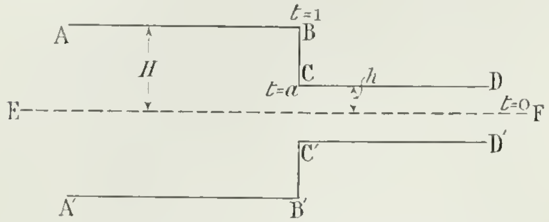


FIG. 12.—Boundary conditions of stepped recess.

The problem is illustrated in Fig. 12, and selecting values of $t$ as shown therein we have by the usual transformation:—

$$\frac{dz}{dt} = \frac{C\sqrt{(t-a)}}{t\sqrt{(t-1)}} \quad . \quad . \quad . \quad . \quad (18)$$

When $t$ is nearly zero, $dz/dt = C\sqrt{a/t}$. Putting $t = R\epsilon^{i\theta}$ the change as $t$ passes through zero is

$$\int_{\pi}^{0}\frac{dz}{dt} = \sqrt{a}C\Big[\log R + i\theta\Big]_{\pi}^{0} = -i\sqrt{a}\pi C$$

corresponding to an increase in $z$ of $ih$; so that

$$C = -h/\sqrt{a}\pi$$

When $t$ is very large, $dz/dt = C/t$, so that the change in $t$ at infinity is $C\Big[\log R + i\theta\Big]_{0}^{\pi} = iC\pi$. This corresponds to an increase in $y$ of $-H$.

Thus $C = -H/\pi$ and so $\sqrt{a} = h/H = 1/m$ . (19)

Integrating Equation (18) with respect to $t$ and determining the constant so that $x = 0$, when $t = a$ and $y = 0$ along the dotted line EF we have:—

$$x + iy = C\left\{\cosh^{-1}\frac{2t-(a+1)}{a-1} + \sqrt{a}\cosh^{-1}\frac{2a-(a+1)t}{(a-1)t}\right\} \quad . \quad (20)$$

Here, as earlier in the paper, a difficulty arises regarding the selection of signs, and it must be settled in a similar manner, viz. by the laborious process of working out a table for a given case and selecting the signs to suit the boundaries. We thus find:—

$$x + iy = \frac{H}{\pi}\left\{\cosh^{-1}\frac{2t-(a+1)}{a-1} + \sqrt{a}\cosh^{-1}\frac{2a-(a+1)t}{(a-1)t}\right\} \quad . \quad (21)$$

with the following rule:—

In evaluating the first term the real part is always to be taken negative, while in the second term the real part must be taken positive. In both cases the imaginary part is always positive.

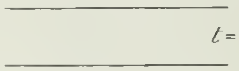


FIG. 13.—Potential conditions for Fig. 12.

The diagram in the plane of $w = \phi + i\psi$ is shown in Fig. 13, from which, as in a previous case, we obtain

$$\phi + i\psi = +0·4(\log t - i\pi)M' \quad . \quad . \quad (22)$$

where $M'$ is the number of ampere-turns acting across the semi-gap.

Thus $F' = +0·4\log t$. and $\phi = 0$ when $t = 1$.

The most interesting portion of the problem is the flux issuing from the vertical surfaces, i.e. between the limits $t = a$ and $t = 1$.

$$\begin{aligned} \text{Here}\quad F' &= +0·4\Big\{-\log a + 0\Big\} = -0·4\log a \\ &= -0·4\log\frac{h^2}{H^2} \\ &= 1·84\log_{10}\frac{H}{h}\text{ referred to }M' \quad . \quad . \quad . \quad (23) \end{aligned}$$

or half this value when referred to the ampere-turns acting across the full gap $2h$.

We may with advantage compare this flux with that issuing from the end surfaces DC, EF of Fig. 7, choosing the dimensions adopted in the previous example.

Then $F' = 0·92\log_{10} H/h = 0·92\log_{10} 3 = 0·44$, as against 0·7 from Fig. 6 (middle curve). Thus the surfaces AB, A′B′ of Fig. 12 shelter the surfaces BC, B′C′ and drive in the end flux, reducing it in the ratio 0·44 : 0·7, as compared with Fig. 7.

Again, the flux springing from the surfaces AB and CD in Fig. 12 will not be quite the same as from EG in Fig. 7, nor the same as that obtained in Section I. For a point some distance along BA from B, $t$ is very large and positive, and then from Equation (21):—

$$x + iy = \frac{H}{\pi}\cosh^{-1}\frac{2t}{a-1} + \frac{h}{\pi}\left\{\cosh^{-1}\frac{H^2+h^2}{H^2-h^2}\right\}$$

so that for the surfaces AB, EF

$$x - \frac{h}{\pi}\cosh^{-1}\frac{H^2+h^2}{H^2-h^2} = -\frac{H}{\pi}\log\frac{4t}{1-a}\text{ (very approx.)}$$

or

$$\frac{\pi x}{H} - \frac{h}{H}\cosh^{-1}\frac{H^2+h^2}{H^2-h^2} - \log\frac{H^2-h^2}{H^2}$$
$$= -\log 4 - \log t = -\log 4 - \frac{F'}{0·4}\text{ [from Eqn. (22)]}$$

---

* Since this paper was written our attention has been called to a problem solved by Dr. C. H. Lees in the *Philosophical Magazine*, 1908, Series 6, vol. 16, p. 734, where the resistance of a conductor shaped like the slot in Fig. 12 is determined. Dr. Lees employs a transformation analogous to Equation (20), but our choice of arbitrary values has led to a form simpler than his. For this reason it seems worth while to retain our equations, instead of adopting his and deducing the geometrical permeance therefrom. The attention of members is, however, called to the paper by Dr. Lees, as an excellent example of the practical application of conjugate functions.

† *Journal I.E.E.*, 1919, vol. 57, pp. 134 and 288.

And thus for the surfaces AB, A′B′

$$F' = \frac{-2\pi}{10}\left\{\frac{x}{H} + \frac{1}{\pi}\left(\log\frac{4H^2}{H^2-h^2} - \frac{h}{H}\log\frac{H+h}{H-h}\right)\right\} \quad (24)$$

$$= \frac{-2\pi}{10}\left\{\frac{x}{H} + \frac{1}{\pi}\left(\log\frac{4m^2}{m^2-1} - \frac{1}{m}\log\frac{m+1}{m-1}\right)\right\} \quad (25)$$

$$= \frac{2\pi}{10}\left\{\frac{x}{H} + P\right\} \text{(say}$$

where $x$ is negative and $P$ represents the *reduction* in the permeance of this part of the gap due to the proximity of the boundary BCD. The equation is therefore similar in form to Equations (3), (6) and (16); and to render the correction $P$ immediately useful its value has been plotted in Fig. 14 against such values of $m$ as would ordinarily arise in practice. It will be noticed that when $m$ exceeds 5, the correction is practically constant and equals 0·43.

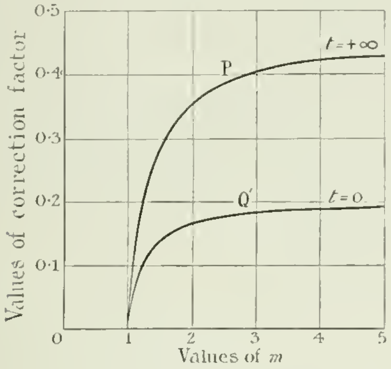


Fig. 14.—Correction factors for Fig. 12.

Dealing similarly with the surface CD, we note that for a point some distance to the right of C, $t$ is nearly zero, and Equation (21) becomes :—

$$x + iy = \frac{H}{\pi}\left\{\cosh^{-1}\frac{H^2+h^2}{H^2-h^2} + \frac{h}{H}\cosh^{-1}\frac{2h^2}{(h^2-H^2)t}\right\}$$

so that, as before,

$$\frac{\pi x}{h} - \frac{H}{h}\log\frac{H-h}{H+h} - \log\frac{4h^2}{H^2-h^2} = -\log t = -\frac{F'}{0\cdot4}$$

or

$$F' = -0\cdot4\left\{\frac{\pi x}{h} - \frac{H}{h}\times\log\frac{H-h}{H+h} - \log\frac{4h^2}{H^2-h^2}\right\} = Q, \text{ say}$$

But this includes the flux along the surface BC, since $x = 0$ when $t = a$. The value of $F'$ along CD is therefore $Q$ minus the value of $F'$ along BC; i.e. for the surfaces CD, C′D′,

$$F' = \frac{-0\cdot4}{2}\left[2\log\frac{H}{h} - \frac{\pi x}{h} + \frac{H}{h}\log\frac{H-h}{H+h} + \log\frac{4h^2}{H^2-h^2}\right]$$

$$= \frac{2\pi}{10}\left[\frac{x}{h} - \frac{1}{\pi}\left(m\log\frac{m+1}{m-1} - \log\frac{4m^2}{m^2-1}\right)\right] \quad . \quad (26)$$

$$= \frac{2\pi}{10}\left[\frac{x}{h} + Q'\right], \text{ say} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

where $Q' = \frac{1}{\pi}\left\{\log\frac{4m^2}{m^2-1} - m\times\log\frac{m+1}{m-1}\right\}$, and the equation is again similar in form to Equations (3), (6), (16) and (25), $Q'$ representing the *increase* in permeance due to the fringing at C, comparable with $1/\pi$ in Equation (3). The correction $Q'$ is shown in the lower curve of Fig. 14, and, for $m = 2$, amounts to 0·1665 instead of $1/\pi$ or 0·317.

## VII. Calculation of Capacity.

Since magnetic flux and electrostatic flux are exact analogues in a rational system of units, it follows that all the cases here considered may be applied to the calculation of the capacity of condensers whose plates are of the shape of the boundaries illustrated in the diagrams. The easiest and most reasonable method of applying this principle is by making use of the quantity called by Heaviside "permittance," and by expressing the electrostatic flux in coulombs.

Examination of such equations as (3), (6), (16), (25) or (26) shows that we may regard the quantity $4\pi/10$ as the specific permeance (or permeability) of air, and the quantity within the brackets as the ratio area/length (or geometric permeance) by which this permeability is multiplied to give the permeance.

Now in the case of capacity we may replace this permeability by the corresponding "permittivity" for air, and replace $F'$, which is in terms of flux per ampere-turn per cm depth, by $C'$ — the corresponding capacity in coulombs per volt per cm depth, i.e. in farads per cm depth.

But the farad is a large unit, and it is more convenient to express $C'$ in microfarads, adopting the appropriate permittivity for air, which is $0\cdot0884 \times 10^{-6}$ microfarads per cm cube. Thus, for example, the capacity of the surfaces AB, EF, in Fig. 12 per cm depth will be :—

$$C' = 0\cdot0884 \times 10^{-6}\left\{\frac{x}{H} + P\right\} \text{ microfarads}$$

and half this value for the surfaces AB, A′B′, where $P$ is to be taken from Fig. 14. And the capacity per cm length of two long, flat, parallel plates, represented in section by AB and CD in Fig. 5, may be taken direct from the upper curve of Fig. 6, by multiplying the required ordinate by $0\cdot221/\pi \times 10^{-5}$.

It is, perhaps, desirable to add that if the dielectric be other than air the equations still apply, provided that the corresponding permittivity be used.

## APPENDIX I.

### Integration of Equation 9.

$$\frac{dz}{dt} = C\frac{\sqrt{t}\sqrt{(t-a)}}{t+1}$$

therefore $$z = C\int\frac{\sqrt{(t^2-at)}}{t+1}dt$$

Let $$t - \frac{a}{2} = \frac{a}{2}\cosh\theta$$

so that $$dt = \frac{a}{2}\sinh\theta\, d\theta$$

Then $$z = \frac{Ca^2}{4}\int \frac{\sinh^2\theta\, d\theta}{\frac{a}{2}(\cosh\theta + 1) + 1}$$

Now write $u$ for $\tanh\frac{\theta}{2}$ and we have

$$d\theta = \frac{2du}{1 - u^2}$$

$$\sinh\theta = \frac{2u}{1 - u^2}$$

$$\cosh\theta = \frac{1 + u^2}{1 - u^2}$$

and $z$ becomes $2Ca^2\int\frac{u^2du}{(1 - u^2)^2(1 + a - u^2)}$.

Resolving the integrand into partial fractions and integrating we obtain :—

$$z = 2Ca^2\left\{\frac{\sqrt{(1 + a)}}{2a^2}\log\frac{\sqrt{(1 + a)} + u}{\sqrt{(1 + a)} - u} + \frac{2 + a}{4a^2}\log\frac{1 - u}{1 + u} + \frac{u}{2a(1 - u^2)}\right\} + K$$

where $K$ is the constant of integration, and transforming back again into terms of $t$ we have :—

$$z = C\left\{\sqrt{t}\sqrt{(t - a)} + \left(1 + \frac{a}{2}\right)\log\frac{2t - a - 2\sqrt{t}\sqrt{(t - a)}}{a} + \sqrt{(1 + a)}\log\frac{\sqrt{(1 + a)t} + \sqrt{t}\sqrt{(t - a)}}{\sqrt{(1 + a)t} - \sqrt{t}\sqrt{(t - a)}}\right\} + K$$

Both $x$ and $y$ vanish when $t = a$, so that $K = 0$.

## APPENDIX II.

### NOTE ON ELLIPTIC FUNCTIONS.

Engineers are not often trained to solve equations involving elliptic functions, so that the notation employed on page 1063 may not be familiar to some of the readers of this paper. It is hoped, therefore, that the following outline of the meaning of the symbols may be of use, for in engineering problems it not infrequently happens that expressions arise involving integrals of the form :—

$$u = \int_0^y (1 - t^2)^{-\frac{1}{2}}(1 - k^2t^2)^{-\frac{1}{2}}dt$$

or $$u = \int_0^\alpha (1 - k^2\sin^2\theta)^{-\frac{1}{2}}d\theta$$

where the second form is derivable from the first by the substitution of $\sin\theta$ for $t$. In these equations $k$, which is always positive and less than 1, is called the modulus of the function ; and if in the first form $y = 1$, or in the second $\alpha = \pi/2$, the integral is said to be complete, and is denoted by the letter $K$. Also $y$ is said to be the sine of the amplitude of $u$, and is generally written $y = sn(u, k)$, or more briefly $y = sn(u)$, when functions having the same modulus are to be understood.

Now it can be shown that $sn(u + 4K) = sn(u)$, so that the function is periodic in the same sense as the sine of an angle is periodic, for $\sin(x + 2\pi) = \sin x$. And just as we say that the function $\sin x$ has a period $2\pi$, so the elliptic function $sn(u)$ may be said to have a real period $4K$.

The "$sn$" is only one of a complete set of such functions, all inter-related, much as the trigonometrical or hyperbolic functions are, but these we must leave the reader to discover for himself. It is sufficient here to remark that if $(k^2 + k'^2) = 1$, then $k'$ is called the "complementary modulus" ; and similar sets of expressions involving $k'$ instead of $k$ can be derived. In this way we obtain a value $K'$ analogous to $K$, such that $K' = \int_0^1 (1 - t^2)^{-\frac{1}{2}}(1 - k'^2t^2)^{-\frac{1}{2}}dt$. But it can be shown that $sn(u + 2iK') = sn(u)$, so that we may look upon $2iK'$ as the imaginary period, in the same sense that $4K$ is the real period of the function $sn(u)$.*

## APPENDIX III.

### DERIVATION OF FIG. 5.

A scale for Fig. 4 was selected in which $d = 8$ and $r = 4$. Then $d/(d + 2r) = k = \frac{1}{2}$. Also, since $r = b(1 - k)/k$, it follows that $b = 4$.

Now the transformation $x + iy = b \times sn(\psi + i\phi)$ may be expanded as follows :—

$$x + iy = \frac{b\{(sn\psi \times cni\phi \times dni\phi) + (sni\phi \times cn\psi \times dn\psi)\}}{1 - k^2sn^2\psi \times sn^2i\phi}$$

and the right-hand side of this equation may be put in terms of elliptic functions of real variables, using Abel's imaginary transformation. Thus :—

$$x + iy = \frac{b\{sn\psi \times dn(\phi, k') + isn(\phi, k') \times cn(\phi, k') \times cn\psi \times dn\psi\}}{cn^2(\phi, k') + k^2sn^2\psi \times sn^2(\phi, k')} \quad \text{(A)}$$

where $k' = \sqrt{(1 - k^2)}$, as in Appendix II. Also, if $sn(\phi, k') = \sin\alpha$ then $\phi = \int_0^\alpha (1 - k'^2\sin^2\theta)^{-\frac{1}{2}}d\theta$.

In order to obtain Fig. 5 we took a set of values of $sn(\phi, k')$ ranging from sin 0° to sin 90°, and combined these with a corresponding set of values of $sn(\psi, k)$ over the same range. Substituting in Equation (A) and equating real and imaginary parts, gives a set of co-ordinates $(x, y)$ for the points of intersection of the $\psi$, $\phi$ lines. The values of $\psi$ and $\phi$ were taken from the published tables. Thus if $sn(\phi, k') = \frac{1}{2}$, then $\phi = \int_0^{30°} (1 - k'^2\sin^2\theta)^{-\frac{1}{2}}d\theta$, which is given in the tables. The values of the co-ordinates of the intersections were then plotted, and from the resulting graph we took readings (by interpolation) of the points of intersection of nine equally-spaced $\psi$ lines with an equal number of equally-spaced $\phi$ lines. The former were taken at 0, $K'/8$, $2K'/8$ . . . $K'$ and the latter at 0, $K/8$, . . . $K$.

---

* For a full discussion of these functions members are refered to WHITTAKER and WATSON, "Modern Analysis," 2nd ed., chap. 22.

Now $2K$ is the potential between the two surfaces, while $K'$ is the limiting value of the flux at the extremity of the surfaces.* Thus the "geometric permeance" is the ratio $K'/2K$, and between each pair of $\phi$ lines the same flux is included, just as between each pair of $\psi$ lines there is a definite magnetic potential difference.

## APPENDIX IV.

### THE METHODS EMPLOYED IN THE PAPER.

The difficulty of dealing with problems such as are considered in this paper, lies in the fact that we are usually given definite boundaries along which the potential is prescribed, and we have to find a potential function to suit the boundaries. The general method employed is that of conformal transformation, and the only direct process at present known is that due to Schwarz and Christoffel. Apart from this, problems have been solved indirectly by selecting a transformation and finding the boundary conditions that it solves. Cases II and V in the paper are examples of this, but the best illustrations are those of Maxwell. The whole subject of conjugate functions and the transformations employed with them is of surpassing interest and enormous importance to the electrical engineer The following short bibliography may therefore be of use to those who wish to pursue the subject further :—

MAXWELL : "Electricity and Magnetism," 2nd edition, chap. 12.

FORSYTH : "Theory of Functions," chaps. 19, 20 and 21, especially pp. 646–649.

CHRISTOFFEL : *Annali di Matematica*, 1867, vol. 1, p. 89.

SCHWARZ : *Journal für die reine und angewandte Mathematik*, 1869, vol. 70, p. 105.

MICHELL : "On the Theory of Free Stream Lines," *Philosophical Transactions*, 1890, ser. A, p. 389.

LOVE : *Proceedings of the Cambridge Philosophical Society*, 1891, vol. 7, p. 175.

LAMB : "Hydrodynamics," chap. 4.

JEANS : "Mathematical Theory of Electricity and Magnetism," 4th edition, p. 266.

J. J. THOMSON : "Recent Researches in Electricity and Magnetism," chap. 3.

RAYLEIGH : *Philosophical Magazine*, 1876, vol. 2, p. 441.

And, in addition, the papers by Carter, Richardson, Lehmann and Lees, references to which have already been given.

---

* See J. J. THOMSON, *loc. cit.*

# THE LEAKAGE FLUX BETWEEN PARALLEL POLE-CORES OF CIRCULAR CROSS-SECTION.[*]

By B. HAGUE, M.Sc., Associate Member.

(*Paper first received 22nd May, and in final form 5th July, 1923.*)

## SUMMARY.

Some of the formulæ used by designers for the purpose of calculating the leakage flux passing between circular pole-cores in salient-pole machines are far from satisfactory, since they cause the flux to be considerably under-estimated. The object of this paper is to draw attention to formulæ and curves from which the permeance of the leakage paths can be found with high accuracy, the results being derived by simple mathematical methods. A critical comparison of the old with the new formulæ is given, illustrated by a numerical example to show the use of the new results in practice.

## INTRODUCTION.

The objects of this short paper are first, to draw attention to certain formulæ which have been suggested for use in design practice to enable the permeance of the leakage field between parallel pole-cores of circular section to be calculated; secondly, to derive from first principles, by the use of simple mathematics, a closely approximate formula; and thirdly, to give a graphical and tabular comparison of the various expressions.

The problem of calculating the leakage flux between the pole-cores of a dynamo is complicated by the following facts: (i) That the poles are of finite length and are attached to a yoke-ring; (ii) that the poles are spaced uniformly and radially round a circle; (iii) that a pole-core is not at a uniform magnetic potential over its whole surface, since it is magnetized by a distributed field-coil carrying the exciting current; and (iv) that the leakage field may be considerably affected by the effects of magnetic saturation in the cores. Hence, accurately to determine the leakage involves the solution of a three-dimensional problem in which the bounding surfaces have a highly complicated distribution of magnetic potential. Since mathematical methods are not sufficiently powerful to enable the exact solution to be obtained, attention must be directed to the provision of approximations having an accuracy sufficient for all practical purposes.

In order to render the problem even approximately soluble, it must first be reduced to two dimensions. In common with other writers on the subject, the author has made the following assumptions:—

(i) The pole-cores are treated as long, parallel, circular cylinders maintained alternately at equal positive and negative magnetic potentials. Variation of magnetic potential along the length of the cores, due to the presence of exciting coils, is ignored; ways of taking such variation approximately into account have been given by various writers[*] and are well known to designers. The surface of a pole-core is therefore taken to be a magnetic equipotential surface.

(ii) As a consequence of (i) the cores are assumed to have a very great permeability compared with that of the surrounding air space in which the leakage of flux takes place.

(iii) The disturbing effects of the presence of pole-shoes and of the yoke on the distribution of the leakage field are neglected.

The permeance calculated under these assumptions will only be accurately applicable to the leakage between the cores in an ideal machine with a flat armature and long, parallel, pole-cores. By means of the designer's artifices just referred to, the results are made to apply approximately to the short, radial cores of an actual salient-pole dynamo.[†]

## HISTORICAL.

The results in use among designers at the present time, by means of which the leakage from circular pole-cores is calculated, are of two kinds according to the means adopted to simplify the mathematical analysis. In the first class, certain assumptions are made concerning the geometrical shape of the lines of force of the field. Thus Dr. Pohl[‡] has given an approximation of this nature by assuming the lines of force to consist of straight lines and arcs of involutes of a circle. Douglas,[§] with much greater approach to the truth, has given a result based on the assumption that the lines of force are sine curves.

Now, in accordance with a principle enunciated by Lord Rayleigh,[‖] the lines of force of a field have the physical property that they are naturally distributed so as to make the permeance of the field a maximum. Hence, the permeance calculated from any assumed distribution of lines of force other than the true distribution must of necessity be too small. If the boundary conditions be given, the true distribution of a two-dimensional field can be found by the method of conjugate functions, but the application of the method when one of the bounding surfaces is curved, as in the present problem, is hindered by almost insuperable mathematical difficulties. This trouble is overcome in the second class of results by obtaining a solution of the leakage problem when the pole-cores are bounded by certain curves, approximately circular in shape, which enable the field to be simply determined. Douglas [*] has given an expression, considered in detail later, for the permeance of the field between pole-cores of very nearly circular section.

---

[*] The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[*] See, for example, C. C. HAWKINS: "The Dynamo," 6th edn., 1922, vol. 1, pp. 513 and 517.

[†] It should be noticed here that the degree of accuracy which is attained in solving the two-dimensional problem is, from the point of view of design practice, necessarily far in excess of the accuracy with which this two-dimensional simplification represents the conditions holding in an actual machine.

[‡] R. POHL: "The magnetic leakage of salient poles," *Journal I.E.E.*, 1914, vol. 52, p. 170.

[§] J. F. H. DOUGLAS: "The approximate determination of the reluctance of an irregular conductor," *Physical Review*, 1914, vol. 4, ser. 2, p. 391.

[‖] See "The Theory of Sound," 2nd edn., 1896, vol. 2, p. 175.

The object of the present paper is to give a result similar to that deduced by Douglas but derived by simpler mathematical methods.

### LEAKAGE FIELD BETWEEN APPROXIMATELY CIRCULAR POLE-CORES.

It occurred to the author that the field could be simply investigated by considering an electrostatic analogy and by making use of an artifice adopted by Maxwell [†] when discussing the electrostatic field due to a grating of thin wires uniformly charged with electricity.

Consider an infinite number of co-planar, equidistant, parallel line charges of infinite length, successive charges being of equal but opposite signs. Then, as is fairly obvious, the equipotential surfaces will be cylinders coaxial with the charges, these surfaces at small distances from the charges being approximately circular cylinders. Even at large distances from the charges the equipotential lines can be shown to be very nearly circles.

It follows, therefore, that if the field due to such a system of parallel line charges can be found, the permeance of the field having any one of the almost circular equipotential surfaces for a boundary can be readily calculated. The following paragraphs will be devoted to the investigation of this problem.

In Fig. 1, let 1, 2, 3 . . . 1′, 2′, 3′ . . . be the points in which the infinitely long line charges cut the plane of the paper normally. Then it is easy to prove that the potential at a point in the plane at a radial distance $r$ from an infinite line charge of linear density $\sigma$ is equal to :—

$$C - 2\sigma \log r$$

where $C$ is a constant determined from the conditions existing at the ends of the line charge.[*]

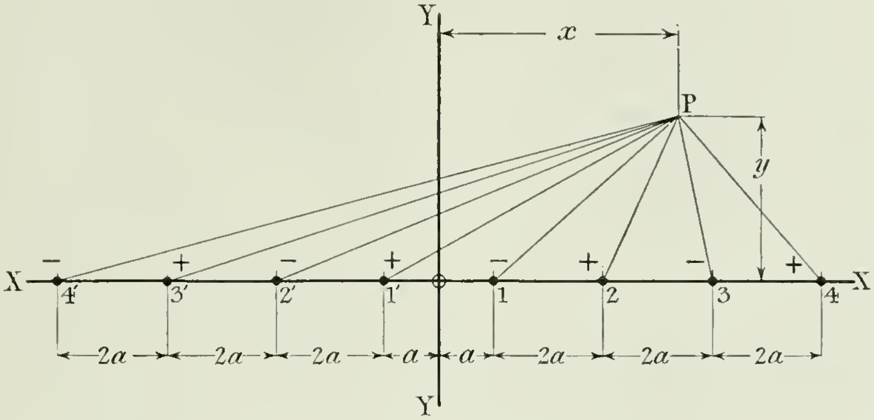


FIG. 1.—Illustrating the co-ordinates used in Equation (1).

The black dots indicate where the alternate positive and negative line charges cut the plane of the paper.

Now potentials are superposable, so that the potential at a point P having the co-ordinates $(x, y)$ is readily obtainable by adding the potentials due to the individual charges. For the pair of charges situated at the points 1′ and 1 the potential is clearly

$$V_1 = 2\sigma \log (r_1/r_1')$$

where the distance $r_1 = 1P$ and $r_1' = 1'P$. The constant $C$ vanishes since the end conditions are similar for the two charges. For the second pair at 2 and 2′ the potential is :—

$$V_2 = -2\sigma \log (r_2/r_2')$$

and, in general, for the $n$th pair

$$V_n = (-1)^{n-1} \times 2\sigma \log (r_n/r_n')$$

in which $r_n = nP$ and $r_n' = n'P$. The total potential is therefore

$$V = 2\sigma \sum_{1}^{\infty} (-1)^{n-1} \log (r_n/r_n') \quad . \quad . \quad (1)$$

---

[*] J. F. H. DOUGLAS: "The reluctance of some irregular magnetic fields," *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, pt. 1, p. 1067.

[†] J. C. MAXWELL: "A Treatise on Electricity and Magnetism," 3rd edn., 1892, p. 310 and Fig. 13 ; also see H. LAMB : "Hydrodynamics," 4th edn., p. 68. For a full discussion of the general theory of the functions used in the solution of the present problem see R. A. SAMPSON : "On Stokes's current function," *Philosophical Transactions of the Royal Society*, A, 1891, vol. 182, p. 449.

[*] J. H. JEANS: "The Mathematical Theory of Electricity and Magnetism," 3rd edn., 1915, p. 68. The logarithm is to the Napierian base.

Now from the geometry of Fig. 1, if $2a$ be the spacing of the charges,

$$\begin{aligned} r_n^2 &= \left\{x - (2n-1)a\right\}^2 + y^2 \\ &= (x^2 + y^2) + (2n-1)^2a^2 - 2(2n-1)ax \\ r_n'^2 &= \left\{x + (2n-1)a\right\}^2 + y^2 \\ &= (x^2 + y^2) + (2n-1)^2a^2 + 2(2n-1)ax \end{aligned}$$

so that, by reduction,

$$r_n^2/r_n'^2 = (m - \zeta)\,(m - \xi)/(m + \zeta)\,(m + \xi) \quad . \quad (2)$$

where $m = 2n - 1$, $\zeta = (x + jy)/a$, $\xi = (x - jy)/a$

$j$ being the positive square root of $-1$.

Inserting the values from Equation (2) in Equation (1) gives :—

$$\begin{aligned} V &= \sigma \sum_{1,3,5,\ldots}^{\infty} (-1)^{(m-1)/2} \log \frac{(m - \zeta)\,(m - \xi)}{(m + \zeta)\,(m + \xi)} \\ &= \sigma \sum_{1,3,5,\ldots}^{\infty} \Big[(-1)^{(m-1)/2} \Big\{\log(m - \zeta) - \log(m + \zeta) \\ &\qquad + \log(m - \xi) - \log(m + \xi)\Big\}\Big] \quad . \quad (3) \end{aligned}$$

Now by expansion in infinite series it can readily be shown [*] that an expression of the form

$$\begin{aligned} &\sum_{1,3,5,\ldots}^{\infty} \Big[(-1)^{(m-1)/2} \Big\{\log(m - \gamma) - \log(m + \gamma)\Big\}\Big] \\ &\quad = -2\left[\gamma\left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \ldots\right)\right. \\ &\qquad + \frac{\gamma^3}{3}\left(1 - \frac{1}{3^3} + \frac{1}{5^3} - \frac{1}{7^3} + \ldots\right) \\ &\qquad \left. + \frac{\gamma^5}{5}\left(1 - \frac{1}{3^5} + \frac{1}{5^5} - \frac{1}{7^5} + \ldots\right) + \text{etc.}\right] \\ &\quad = -\log \tan \frac{\pi}{4}(1 + \gamma) \end{aligned}$$

Writing $\zeta$ and $\xi$ for $\gamma$ and substituting in Equation (3) gives :—

$$V = -\sigma \log \left[\tan \frac{\pi}{4}(1 + \zeta) \times \tan \frac{\pi}{4}(1 + \xi)\right]$$

Inserting the values of $\zeta$ and $\xi$ from Equation (2) and making use of the well-known relationships between trigonometric functions of a complex number and the real hyperbolic and circular functions, gives finally, for the potential [†] at any point P due to the infinite number of successive positive and negative line charges :—

$$V = -\sigma \log \left[\frac{\cosh(\pi y/2a) + \sin(\pi x/2a)}{\cosh(\pi y/2a) - \sin(\pi x/2a)}\right] \quad . \quad (4)$$

## EQUIPOTENTIALS AND LINES OF FORCE.

To determine the distribution of the field the equations to the equipotentials and the lines of force must be found. On any line of constant potential, $V$ is constant. Thus transforming Equation (4) gives :—

$$\frac{\cosh(\pi y/2a)}{\sin(\pi x/2a)} = \frac{(\epsilon^{-V/\sigma} + 1)}{(\epsilon^{-V/\sigma} - 1)} = A$$

where $A$ is a parameter, constant on any equipotential line but varying from line to line; the equipotentials are therefore given by the equation

$$\cosh \frac{\pi y}{2a} = A \sin \frac{\pi x}{2a} \quad . \quad . \quad . \quad . \quad (5)$$

By differentiation of Equation (5) the slope at any point is

$$\frac{dy}{dx} = \frac{1}{\tanh(\pi y/2a) \times \tan(\pi x/2a)}$$

and, since the lines of force cut the equipotentials at right angles, the value of $dy/dx$ on them must be

$$\frac{dy}{dx} = -\tanh \frac{\pi y}{2a} \times \tan \frac{\pi x}{2a}$$

which on integration gives as the equation to the lines of force :—

$$\sinh \frac{\pi y}{2a} = B \cos \frac{\pi x}{2a} \quad . \quad . \quad . \quad . \quad (6)$$

where $B$ is an arbitrary constant.

The field of force determined by Equations (5) and (6) is plotted in Fig. 2,[*] from which it will be observed how closely the equipotential lines in the neighbourhood of the charges approach to the circular shape.

## PERMEANCE.

Reverting now to the corresponding magnetic problem, let Equation (4) represent the magnetic potential due to an infinite row of thin wires, successive wires having equal and opposite magnetic polarities. Fig. 2 then shows the corresponding magnetic field.

From the potential given in Equation (4) the magnetic field strength is readily calculable. The component parallel to the axis of $x$ is :—

$$H_x = -\frac{\partial V}{\partial x} = \frac{\pi\sigma}{a}\left[\frac{\cosh(\pi y/2a) \times \cos(\pi x/2a)}{\cosh^2(\pi y/2a) - \sin^2(\pi x/2a)}\right] \quad . \quad (7a)$$

while that parallel to the $y$ axis is :—

$$H_y = -\frac{\partial V}{\partial y} = -\frac{\pi\sigma}{a}\left[\frac{\sinh(\pi y/2a) \times \sin(\pi x/2a)}{\cosh^2(\pi y/2a) - \sin^2(\pi x/2a)}\right] \quad . \quad (7b)$$

The total field strength at the point P is thus :—

$$H = (H_x^2 + H_y^2)^{\frac{1}{2}} = \frac{\pi\sigma}{a}\left[\frac{\sinh^2(\pi y/2a) + \cos^2(\pi x/2a)}{\cosh^2(\pi y/2a) - \sin^2(\pi x/2a)}\right] \quad . \quad (7c)$$

in the direction $\phi$ relative to the $x$ axis, $\phi$ being given by

$$\tan \phi = \frac{H_y}{H_x} = -\tanh \frac{\pi y}{2a} \times \tan \frac{\pi x}{2a} \quad . \quad (7d)$$

---

[*] Sir G. GREENHILL: "Differential and Integral Calculus," 2nd edn., 1891, pp. 227 and 237.

[†] For a verification of this expression by the method of images, see J. KUNZ and P. L. BAYLEY: "Some applications of the method of images," *Physical Review*, 1921, vol. 17, p. 147.

[*] For a similar diagram see R. S. BROWN: "Use of the tangent chart for solving transmission line problems," *Journal of the American Institute of Electrical Engineers*, 1921, vol. 40, p. 854.

At any point on the axis of $y$ the field strength has the value

$$\frac{\pi\sigma}{a\cosh(\pi y/2a)}$$

from Equation ($7c$) and is parallel to the axis of $x$. From Fig. 2 it is obvious that by integrating this field strength between the limits of $-\infty$ and $+\infty$ for $y$, half the flux which enters the negative charge (or south pole) situated at the point $(a, 0)$ is obtained. Hence, per unit height perpendicular to the plane of the diagram, the total flux entering this pole is :—

$$-\frac{2\pi\sigma}{a}\int_{-\infty}^{\infty}\frac{dy}{\cosh(\pi y/2a)} = -4\pi\sigma$$

This also follows at once by the simple application of Gauss's theorem to an equipotential surface surrounding the pole, a minus sign being prefixed to indicate that the flux is entering the pole. Since this flux crosses every equipotential surface lying between the pole at $(a, 0)$ and the zero potential planes of symmetry represented by the lines $x = 0$ (or YY) and $x = 2a$, (or Y′Y′), it follows that the permeance of the field between the zero potential planes YY, Y′Y′ in Fig. 2 and any equipotential chosen to represent an approximately circular pole-core passing through a point $x_1$ is easily obtainable.

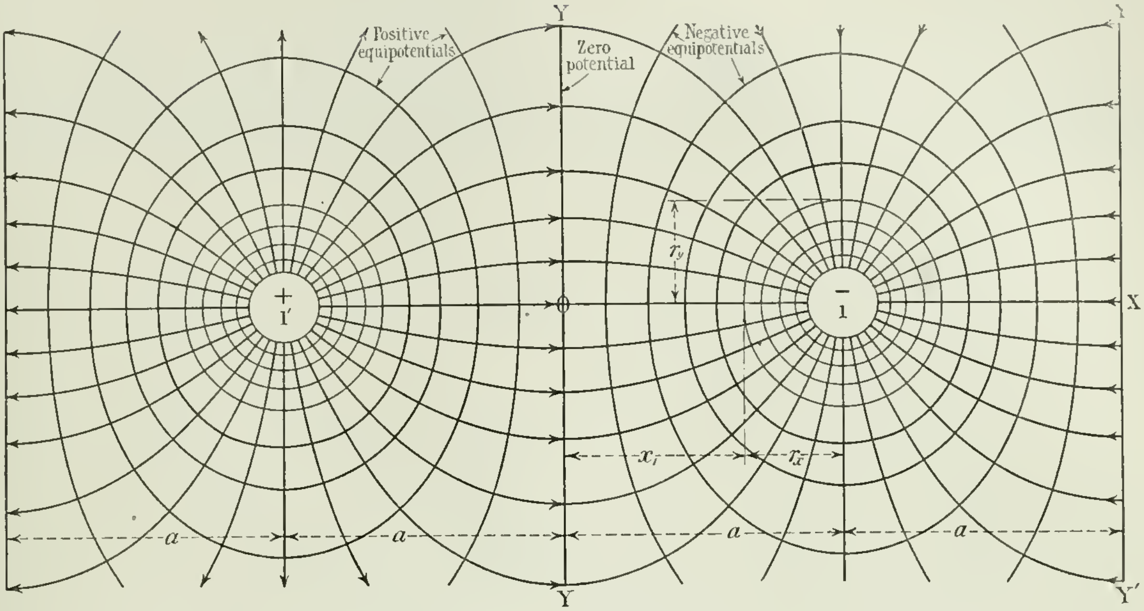


Fig. 2.—Diagram of the lines of force and equipotential surfaces due to the line charges of Fig. 1.

Table 1.

| | Arnold's formula | Pohl's formula | Pohl's formula + 2 | Douglas's sine approx. | Douglas's exact formula | Approximation : Equation (8) | | | |
|---|---|---|---|---|---|---|---|---|---|
| $r/a$ | P | P | P | P | P | $r_x/a$ | $r_y/a$ | $r_y/r_x$ | P |
| 0·05 | $0·3644_1$ | $0·3245_9$ | $2·3245_9$ | 1·90 | 1·9409 | 0·05 | $0·050_0$ | $1·00_0$ | 1·9409 |
| 0·10 | $0·7511_1$ | $0·6687_9$ | $2·6687_9$ | 2·40 | 2·4668 | 0·10 | $0·100_4$ | $1·00_4$ | 2·4716 |
| 0·20 | 1·6039 | 1·4338 | 3·4338 | 3·24 | 3·3952 | 0·20 | $0·203_3$ | $1·01_7$ | 3·4098 |
| 0·30 | 2·5955 | 2·2753 | 4·2753 | 4·20 | 4·3493 | 0·30 | $0·317_7$ | $1·05_9$ | 4·4036 |
| 0·40 | 3·7805 | 3·4012 | 5·4012 | 5·10 | 5·4403 | 0·40 | $0·429_2$ | $1·07_3$ | 5·5893 |
| 0·50 | 5·2478 | 4·7394 | 6·7394 | 6·40 | 6·7731 | 0·50 | $0·560_7$ | $1·12_1$ | 7·1300 |
| 0·60 | 7·1491 | 6·4910 | 8·4910 | 8·10 | 8·5183 | 0·60 | $0·713_5$ | $1·18_9$ | 9·3184 |

From Equation (4), putting $x = x_1$ and $y = 0$ gives as the potential of the pole-core :—

$$V_{y=0} = -\sigma\log\left[\frac{1+\sin(\pi x_1/2a)}{1-\sin(\pi x_1/2a)}\right]$$

the $x$ semi-diameter of the core being $r_x = a - x_1$. With this value of potential and $x = a$, the $y$ semi-diameter of the core is found to be $y_1 = r_y$ from the same equation; an idea of the degree of circularity of the pole-core is thus obtained. The permeance between this equipotential core and the planes of symmetry is then

$$\mathbf{P} = -\frac{4\pi\sigma}{V_{y=0}} = \frac{4\pi}{\log\left[\dfrac{1+\sin(\pi x_1/2a)}{1-\sin(\pi x_1/2a)}\right]} \quad . \quad (8)$$

From this expression it is easy to calculate the leakage permeance between an approximately circular pole-core and the planes YY, Y′Y′, by merely inserting values of $x_1/a$. The results of this calculation are shown in Table 1 and in Fig. 3, $\mathbf{P}$ being given as a function of $r_x/a$ and $r_y/a$.

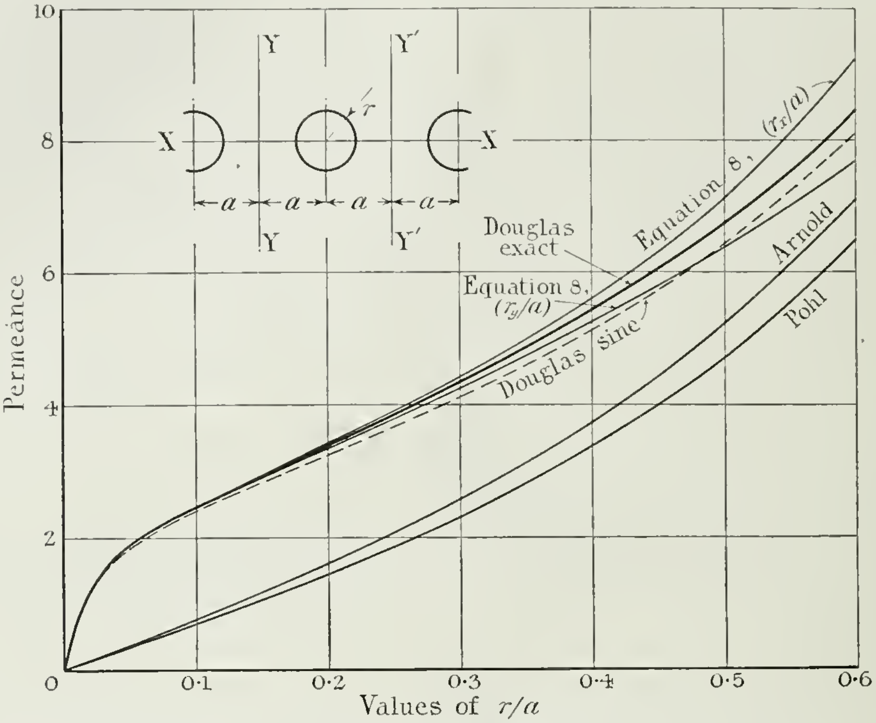


FIG. 3.—Permeance of the leakage field between parallel circular pole-cores.

Ordinates give the permeance $\mathbf{P}$ of the field between the core and the planes YY, Y′Y′ per unit height of the pole-core. $r$ is the semi-diameter of a truly circular pole; $r_x$, $r_y$ are the semi-diameters, parallel to $x$ and $y$ axes respectively, of a slightly oval pole.

### COMPARISON OF FORMULÆ.

For the purpose of comparison, Table 1 and Fig. 3 contain the results obtained from other formulæ which have been proposed for the calculation of the leakage flux from circular cores.

The method devised by Arnold * is very widely used by designers. The circular core is first reduced to a square core of equal cross-sectional area; the lines of leakage flux from this "equivalent square" are then supposed to consist of circular quadrants starting from the flank faces continued by straight lines passing across to the interpolar plane. The side leakage lines from pole to pole are taken as being straight. If $2b$ be the side of the square, $b = \sqrt{(\pi/4)}r$, and the permeance of the field between the core and the interpolar planes is :—

$$\mathbf{P} = 4\left[\frac{b/a}{1-(b/a)} + \frac{2}{\pi}\log\left\{1 + \tfrac{1}{2}\pi\frac{b/a}{1-(b/a)}\right\}\right]$$

Dr. Pohl * has assumed that each line of force is composed of a portion of an involute springing from the circular core and a straight line parallel to OX. Pohl's formula, expressed in the notation of this paper, is :—

$$\mathbf{P} = 4\sqrt{\left\{\frac{2r/a}{1-(r/a)}\right\}}\arctan\left\{\tfrac{1}{4}\pi\sqrt{\frac{2r/a}{1-(r/a)}}\right\}$$

where $r$ is the radius of the pole-core and $2a$ the distance between the centres of successive cores.

The leakage field according to both the preceding assumptions is far too cramped laterally and, in accordance with Rayleigh's principle, will have much too low a permanence. Comparison of the curves in Fig. 3 will serve to confirm this fact: it is noteworthy that Arnold's result is better than Pohl's, but both are particularly in error for values of $r/a$ encountered in design practice. Mr. S. Neville has pointed out to the author that (Pohl's result + 2) is very close to the true value in the working range of $r/a$ (see Table 1).

To avoid undue lateral contraction of the field,

---

* E. ARNOLD: "Die Wechselstromtechnik," 2nd edn., 1913, vol. 4, p. 87; also C. C. HAWKINS, S. P. SMITH and S. NEVILLE: "Papers on the Design of Alternating-current Machinery," p. 70.

* R. POHL, *loc. cit.*, Fig. 4 and Equation (6).

Douglas * suggested that the lines of force might be closely represented by suitably chosen sine curves and, with this assumption, he calculated the permeance. As can be seen from Table 1 and the curve plotted in Fig. 3, this assumption leads to values which are nearly correct.

To show the nature of the three field distributions just described, Fig. 4 has been prepared. Four quadrants are shown containing the true field plotted from Equation (6); superposed thereon in three of the quadrants are the field distributions suggested by Arnold, Pohl and Douglas. It will be seen that the last is the only one which bears the least resemblance to the real field and gives the closest approximation to the actual permeance.

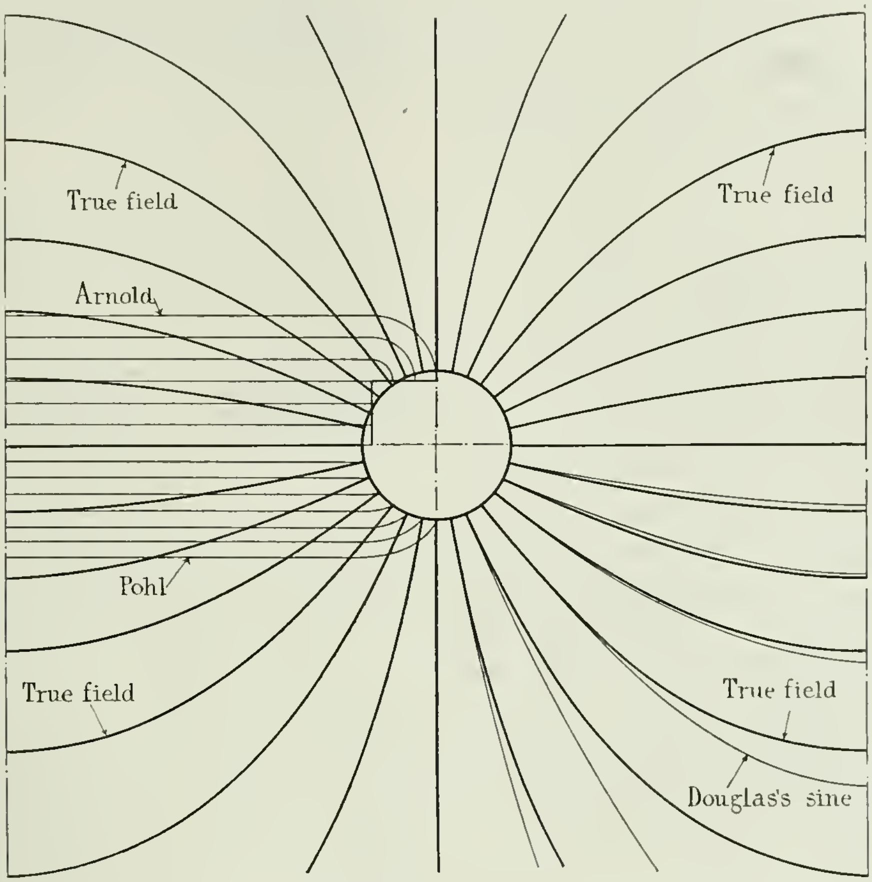


FIG. 4.—Comparison of the actual field distribution from circular cores with the various approximate distributions hitherto suggested.

Heavy lines are the true lines of force. Lighter lines are :—
Left upper quadrant : Arnold's square-pole approximation.
Left lower quadrant : Pohl's involute approximation.
Right lower quadrant : Douglas's sine-curve approximation.

A little later, Douglas produced an expression for circular poles arrived at in the following way. Deriving first, by means of conjugate functions, a formula for the potential due to line charges, exactly equivalent to that given in the present paper, he applied a small correction term intended to make the equipotential curves much more nearly circular. His result thus applies very exactly to truly circular poles, and from the potential formula an expression for the permeance is found in the form :—

$$\mathbf{P} = 2\pi\left[\frac{\cot^2\dfrac{\pi r}{4a} + \coth^2\dfrac{\pi r}{4a}}{\coth^2\dfrac{\pi r}{4a}\log\cot\dfrac{\pi r}{4a} + \cot^2\dfrac{\pi r}{4a}\log\coth\dfrac{\pi r}{4a}}\right]$$

which is tabulated as the " exact " formula in Table 1, since it represents the most accurate result which present mathematical methods seem capable of securing.*

Referring now to the permeance formula obtained in

---

* J. F. H. DOUGLAS: *Physical Review, loc. cit.*

* J. F. H. DOUGLAS: *Transactions of the American Institute of Electrical Engineers, loc. cit.*, Equation (46) and Fig. 23. Dr. Douglas has asked the author to draw attention to two important errors in the formula as printed in his paper. The + sign in the denominator is wrongly printed as −, and the formula when corrected in this respect gives the permeance of only one-quarter of the leakage flux per pole. The plotted results are for the permeance of the total flux per pole, and the external multiplier should be $2\pi$, as given above, and not $\pi/2$ as in Dr. Douglas's paper. Thanks are due to Dr. Douglas for his kindness and courtesy in correspondence relating to this matter and for his encouragement while this paper was in preparation.

Equation (8), it will be seen that when the results are plotted as a function of $r_x/a$ they are slightly higher than Douglas's exact values; while when plotted as a function of the corresponding $r_y/a$ for the slightly oval equipotential curves they are a little too low. In practical work an estimate can be made between the two curves, slightly nearer to the former than to the latter; or alternatively the upper curve can be used to allow for a margin in design.

It should be pointed out here that, with one exception, the figures in Table 1 are calculated to a degree of accuracy far in excess of practical requirements in design, the object being to show the extent of agreement between the various formulæ. The exception mentioned is the sine-curve approximation of Douglas, which cannot be calculated entirely from mathematical tables, since at one stage it requires the performance of a graphical integration. For design purposes use will be made of values taken direct from the curves of Fig. 3.

### NUMERICAL EXAMPLE.

In order to show how to use the results collected in this paper, a numerical example will now be worked out. The process of calculating the leakage flux from slightly divergent poles as given by Arnold * and widely used by designers will, for the purpose of illustration, be employed. It should be clearly understood that no attempt is made to justify Arnold's method of calculation, the object being merely to show the relative value of the various permeance formulæ. Briefly the method is to take the poles as having parallel cores with a pitch equal to the average pole-pitch of the actual cores in the machine. Since the cores are magnetized by a coil they are subjected to a magnetomotive force which increases uniformly from a minimum at the base of the pole to a maximum at the shoe. It is assumed to be sufficiently correct to suppose that the core leakage is produced by the average magnetomotive force, i.e. by $4\pi AT/(10 \times 2)$, where $AT$ is the number of ampere-turns required for the gap, teeth and armature core.

The following particulars relate to a 300-kVA, 3 000-volt, three-phase, 50-period alternator with a rotating-pole system having 18 poles. The diameter of the pole-ring at the base of the poles being 141·0 cm, and the height of the pole-cores being 16 cm, gives as the pole-pitch half-way up the cores $2a = \pi(141 + 16)/18 = 27 \cdot 4$ cm. The pole-core diameter being $2r = 15 \cdot 7$ cm, gives for the ratio $r/a$ the value $15 \cdot 7/27 \cdot 4 = 0 \cdot 577$. For the production of a flux per pole of 2·68 megalines it was found that 5 800 ampere-turns per pole were required for the air-gap, armature core and teeth. The effective magnetomotive force producing pole-core leakage is then $0 \cdot 4\pi \times 5\,800/2 = 3\,650$ C.G.S. units. If **P** be the permeance per cm height of the pole-core corresponding to the above value of $r/a$, the leakage flux per pole is $3\,650 \times 16\mathbf{P} = 58\,400\mathbf{P}$ lines or $0 \cdot 0584\mathbf{P}$ megalines. Values of **P** have been taken from Fig. 3 for each of the methods discussed in this paper, the results being set forth in Table 2.

TABLE 2.

| Method | Value of **P** for $r/a = 0 \cdot 577$ | Leakage flux per pole, in megalines | Ratio of approximate to true flux |
|---|---|---|---|
| Arnold .. .. .. .. .. | 6·70 | 0·391 | 0·827 |
| Pohl .. .. .. .. .. | 6·09 | 0·356 | 0·753 |
| (Pohl + 2) .. .. .. .. | 8·09 | 0·472 | 0·999 |
| Douglas's sine .. .. | 7·75 | 0·452 | 0·957 |
| Douglas's exact .. .. | 8·10 | 0·473 | 1·000 |
| Equation (8), $r_x/a$ .. | 8·80 | 0·514 | 1·086 |
| Equation (8), $r_y/a$ .. | 7·40 | 0·432 | 0·914 |

From these results it will be observed how seriously the leakage is under-estimated by the methods of Arnold and Pohl, even in such an example as the present which, owing to the large value of $r/a$, is particularly favourable to them. It should be noted in passing how very closely (Pohl + 2) is capable of giving the leakage. The calculated value from the curve for $r_x/a$ provides in this example a margin of 8·6 per cent; the average of this result with that obtained from the curve $r_y/a$ is, however, for such a value of $r/a$, exactly correct.

---

* ARNOLD, *loc. cit.*, and also HAWKINS, SMITH and NEVILLE, *loc. cit.*

# THE EFFECT OF SHEARING STRESS ON THE SPAN CALCULATIONS OF A SUSPENDED CABLE.[*]

By Professor TAKASHI OHTSUKI.

(*Paper first received 29th December,* 1922, *and in final form 30th April,* 1923.)

## SUMMARY.

The paper presents the complete equation of a suspended cable, taking into account its density, elasticity and rigidity, and determines the extent to which the effect of shearing stress should be considered for practical span calculations.

The criterion of the importance of flexural rigidity can be written in the form

$$\varepsilon = 100 \times 2\gamma = 100 \frac{Ed^2D^3}{\rho(S/2)^6} \text{ per cent}$$

where $\varepsilon$ is the percentage error caused by neglecting flexural rigidity in calculating the span from the usual formulæ, and $\gamma = w_0^2 E\mathbf{I}_0/T_0^3$. Here $d$ is the diameter of the wire, $\rho$ the volume density, $w_0$ the linear density, $\mathbf{I}_0$ the moment of inertia of the section, all in the unstretched condition, $E$ Young's modulus, $T_0$ the lowest tension, $D$ the deflection and $S$ the span.

The ordinary catenary equation is sufficiently accurate for most practical purposes, but when $\lambda < 2\gamma$ with the lower tension, where $\lambda = T_0/EQ$ and $Q$ is the cross-sectional area, the effect of flexural rigidity is more important than that of elasticity.

## TABLE OF CONTENTS.

I. Introduction.
II. Equations of a suspended cable, taking into account elasticity and rigidity.
III. Practical formulæ for dip, tension, length and temperature effect.
IV. Numerical examples.
V. Conclusion.

## I. INTRODUCTION.

Several formulæ have been published by various authorities for the calculation of cable span, the form of a suspended cable being assumed to be a parabola, a catenary[†] or an elastic catenary.[‡] These formulæ are, in general, based on the assumption that the cable is perfectly flexible. They are sufficiently accurate for ordinary practical purposes of span calculations in such a case as an electric transmission line. But when the cross-section of the cable is comparatively large and the tension adopted is not high, it will be more reasonable to take into account its rigidity in the equations representing the form of the suspended cable. In the present paper the cable is considered to be a substance having elasticity and rigidity, and the equations represent its correct form, for which the new working formulæ as to dip, tension, etc., are shown. In addition, the extent to which the effect of shearing stress should be taken into account for span calculations is considered.

## II. EQUATIONS OF A SUSPENDED CABLE, TAKING INTO ACCOUNT ELASTICITY AND RIGIDITY.

Let ACB in Fig. 1 represent a wire suspended between two points A and B on the same level.

Taking an elemental length $ds$ at any point P on the wire, for the condition of equilibrium of the tangential and vertical forces we have the following equations respectively :—

$$dT - Ud\psi - wds \sin \psi = 0 \quad . \quad . \quad . \quad (1)$$

$$dU + Td\psi - wds \cos \psi = 0 \quad . \quad . \quad . \quad (2)$$

where $T$ = tangential tension at P ;
$U$ = shearing stress on the cross-section at P ;
$w$ = linear density of the wire in its stretched condition ;
$s$ = length of wire from the lowest point C to P in its stretched condition ; and
$\psi$ = the deflection of $T$ from the horizontal.

Remembering that $M = E\mathbf{I}\dfrac{d\psi}{ds}$

we have $U = -\dfrac{dM}{ds} = -E\mathbf{I}\dfrac{d^2\psi}{ds^2}$

where $M$ = bending moment against $U$ ;
$E$ = Young's modulus of elasticity ; and
$\mathbf{I}$ = moment of inertia of the section about its horizontal axis in the stretched condition.

Substituting these values in Equations (1) and (2), the following fundamental differential equations are established :—

$$\frac{dT}{ds} + E\mathbf{I}\frac{d^2\psi}{ds^2}\frac{d\psi}{ds} = w \sin \psi \quad . \quad . \quad . \quad (3)$$

$$T\frac{d\psi}{ds} - E\mathbf{I}\frac{d^3\psi}{ds^3} = w \cos \psi \quad . \quad . \quad . \quad (4)$$

---

[*] The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] The practical formulæ based on the catenary are completely developed and plotted in curves for various materials of cable by Mr. E. Parry in his paper on "Cable Spans," *Proceedings of the New Zealand Society of Civil Engineers*, 1917.

[‡] Dr. S. Noda has very conveniently developed the expressions for an elastic catenary into practical formulæ in terms of the maximum tension at the suspended points, in his paper "On the Formulæ for Calculating Wire Spans," *Journal of the Institute of Electrical Engineers of Japan*, 1910. Furthermore, with respect to allowances for the elastic property of wires, see C. A. PIERCE, F. J ADAMS and G. I. GILCHREST : "Theory of the Non-Elastic and Elastic Catenary as Applied to Transmission Lines," *Proceedings of the American Institute of Electrical Engineers*, 1913, vol. 32, pt. 2, p. 1373.

Although it would be impossible to obtain its complete solution, we may be able to determine the equation if we ascertain the correction term.

(3) × cos $\psi$ − (4) × sin $\psi$ . . .

$$d(T\cos\psi) + E\mathbf{I}d\left(\frac{d^2\psi}{ds^2}\sin\psi\right) = 0 \quad . \quad . \quad (5)$$

If we assume **I** to be constant, by integrating (5) we have :—

$$T\cos\psi + E\mathbf{I}\left(\frac{d^2\psi}{ds^2}\sin\psi\right) = T_0 \quad . \quad . \quad (6)$$

where $T_0$ is the horizontal tension at the lowest point C.

On the other hand :—

(3) × sin $\psi$ + (4) × cos $\psi$ . . .

$$d(T\sin\psi) - E\mathbf{I}d\left(\cos\psi\frac{d^2\psi}{ds^2}\right) = wds \quad . \quad . \quad (7)$$

The second terms in Equations (6) and (7) correspond to the correction for flexural rigidity.

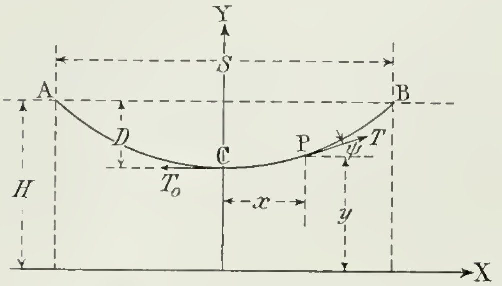


FIG. 1.—System of a suspended wire (side view).

If we omit these terms and assume $w$ to be constant, we have :—

$$\begin{cases} T\cos\psi = T_0 & . \quad . \quad . \quad . \quad . \quad . \quad (6a) \\ d(T\sin\psi) = wds & . \quad . \quad . \quad . \quad . \quad (7a) \end{cases}$$

Therefore $$s = \frac{T_0}{w}\tan\psi \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

which is the well-known equation of a catenary.

Now let $w_0$ and $\mathbf{I}_0$ be the corresponding values of $w$ and **I** in the unstretched condition. Then we have, generally :—

$$w = \frac{w_0}{1 + (T/EQ)}\,; \quad \mathbf{I} = \frac{\mathbf{I}_0}{[1 + (T/mEQ)]^4}$$

where $Q$ is the cross-sectional area of the wire and $m$ Poisson's ratio for the material.

But Poisson's ratio $m = 4$ (approx.) for many metals, so that, retaining the first power of $T/EQ$, $w$ and **I** are nearly equally affected ; and even if the wire is stressed to half its elastic limit, $T/EQ$ does not exceed 1/1 000 for copper or aluminium, so that $w$ and **I** are affected by less than 1 part in 1 000.

This being the case, we may rewrite Equation (7) in the form

$$\left(1 + \frac{T}{EQ}\right)d(T\sin\psi) - E\mathbf{I}_0 d\left(\cos\psi\frac{d^2\psi}{ds^2}\right) = w_0 ds \quad . \quad (7b)$$

Integrating both sides of Equation (7$b$) we obtain :—

$$T\sin\psi + \frac{1}{EQ}\int Td(T\sin\psi) - E\mathbf{I}_0\cos\psi\frac{d^2\psi}{ds^2} = w_0 s + C \quad (9)$$

Although the second term on the left-hand side of Equation (9) gives the correction for an elastic property, we cannot obtain its particular integral, while we do not know the correct equation required.

But since its value is so small, at a first approximation we may be able to substitute the value of $T$ given by Equation (6$a$) for this correction term.

Then we have :—

$$T\sin\psi + \frac{T_0^2}{EQ}\int\sec^3\psi d\psi - E\mathbf{I}_0\cos\psi\frac{d^2\psi}{ds^2} = w_0 s + C$$

$$\text{Therefore } T\sin\psi + \frac{T_0^2}{2EQ}[\sec\psi\tan\psi + gd^{-1}\psi]$$
$$- E\mathbf{I}_0\cos\psi\frac{d^2\psi}{ds^2} = w_0 s \quad . \quad (10)$$

It is clear that the integration constant becomes zero in the present case.

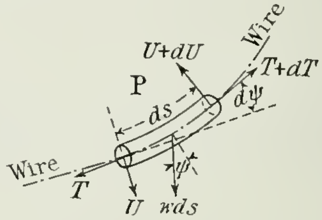


FIG. 2.—Exaggerated force diagram at a point P.

As a second approximation, substituting for $T$ in the above equation the value given in Equation (6), we have :—

$$s = \frac{T_0}{w_0}\tan\psi + \frac{T_0^2}{2w_0 EQ}[\sec\psi\tan\psi + gd^{-1}\psi]$$
$$- \frac{E}{w_0}\frac{d^2\psi}{ds^2}[\mathbf{I}\sin\psi\tan\psi + \mathbf{I}_0\cos\psi] \quad . \quad (11)$$

The effect of stretch being small, we may quite legitimately neglect it in examining the effect of flexural rigidity to the first order of smallness.

Assuming $\mathbf{I} = \mathbf{I}_0$ in the last term of Equation (11), we have :—

$$s = \frac{T_0}{w_0}\tan\psi + \frac{T_0^2}{2EQw_0}[\sec\psi\tan\psi + gd^{-1}\psi]$$
$$- \frac{E\mathbf{I}_0}{w_0}\sec\psi\frac{d^2\psi}{ds^2} \quad . \quad (11a)$$

In order to evaluate this correction term, taking the equation of a catenary [Eqn. (8)] and putting $w = w_0$ as a first approximation, we obtain :—

$$\frac{d\psi}{ds} = \frac{w_0}{T_0}\cos^2\psi$$

$$\frac{d^2\psi}{ds^2} = -\frac{2w_0^2}{T_0^2}\cos^3\psi\sin\psi$$

The first approximate correction is :—

$$\begin{aligned} K_1 &= -\frac{E\mathbf{I}_0}{w_0}\sec\psi\,\frac{d^2\psi}{ds^2} \\ &= \frac{w_0E\mathbf{I}_0}{T_0^2}\sin 2\psi\cos\psi \quad . \quad . \quad . \quad (12) \end{aligned}$$

Therefore the required equation will be :—

$$\begin{aligned} s = \frac{T_0}{w_0}\tan\psi + \frac{T_0}{2w_0EQ}[\sec\psi\tan\psi + gd^{-1}\psi] \\ + \frac{w_0E\mathbf{I}_0}{T_0^2}\sin 2\psi\cos\psi \quad . \quad (13) \end{aligned}$$

Then the second approximate term, $K_2$, will be ascertained in the same way for the curve represented by Equation (13).

Neglecting the second and higher powers of $T_0/EQ$ and $w_0^2E\mathbf{I}_0/T_0^3$ and their products, we get :—

$$\begin{aligned} K_2 &= \frac{w_0E\mathbf{I}_0}{T_0^2}\sin 2\psi\cos\psi\Big[1 - \frac{3T_0}{2EQ}\sec\psi \\ &\qquad - \frac{E\mathbf{I}_0w_0^2}{T_0^3}(27\cos^2\psi - 14)\cos^3\psi\Big] \\ &\risingdotseq \frac{w_0E\mathbf{I}_0}{T_0^2}\sin 2\psi\cos\psi\Big[1 - \frac{3T_0}{2EQ}\sec\psi \\ &\qquad - \frac{14w_0^2E\mathbf{I}_0}{T_0^3}\cos 2\psi\cos^3\psi\Big] \quad . \quad (14) \end{aligned}$$

which is not appreciably different from $K_1$, for $T_0/EQ$ and $w_0^2E\mathbf{I}_0/T_0^3$ are negligibly small compared with unity in the majority of cases.

Consequently we may say that even if the third approximate correction, $K_3$, be obtained for the second approximate equation, there would be no appreciable difference between $K_2$ and $K_3$, and so on. Therefore we may regard Equation (13) as being the required equation of an elastic catenary, taking into account the rigidity of the substance.

In terms of Cartesian co-ordinates we get :—

$$\left.\begin{aligned} dx &= ds\cos\psi \\ &= \frac{T_0}{w_0}\sec\psi\Big(1 + \frac{T_0}{EQ}\sec\psi\Big)d\psi \\ &\qquad + \frac{2w_0E\mathbf{I}_0}{T_0^2}(3\cos^2\psi - 2)\cos^2\psi d\psi \\ x &= \frac{T_0}{w_0}\Big[gd^{-1}\psi + \frac{T_0}{EQ}\tan\psi\Big] \\ &\qquad + \frac{w_0E\mathbf{I}_0}{4T_0^2}[\psi + \sin 2\psi(\tfrac{7}{2} - 3\sin^2\psi)] \end{aligned}\right\} \quad . \quad (15)$$

Similarly

$$\left.\begin{aligned} dy &= ds\sin\psi \\ &= \frac{T_0}{w_0}\sec\psi\tan\psi\Big(1 + \frac{T_0}{EQ}\sec\psi\Big)d\psi \\ &\qquad + \frac{2w_0E\mathbf{I}_0}{T_0^2}(3\cos^2\psi - 2)\sin\psi\cos\psi d\psi \\ y &= \frac{T_0}{w_0}\Big(\sec\psi + \frac{T_0}{2EQ}\tan^2\psi\Big) \\ &\qquad + \frac{w_0E\mathbf{I}_0}{4T_0^2}(4\sin^2\psi - 6\sin^4\psi) \end{aligned}\right\} \quad . \quad (16)$$

The integration constants for $x$ and $y$ are zero, if the $y$-axis is taken through the lowest point C and the $x$-axis is chosen so as to be a distance $T_0/w_0$ below the point $C$.

Then the required form of the suspended wire is given by the following formulæ in Cartesian co-ordinates :

$$\left.\begin{aligned} x &= \frac{T_0}{w_0}\Big[gd^{-1}\psi + \frac{T_0}{EQ}\tan\psi \\ &\qquad + \frac{w_0^2E\mathbf{I}_0}{4T_0^3}\{\psi + \sin 2\psi(\tfrac{7}{2} - 3\sin^2\psi)\}\Big] \\ y &= \frac{T_0}{w_0}\Big[\sec\psi + \tfrac{1}{2}\frac{T_0}{EQ}\tan^2\psi \\ &\qquad + \frac{w_0^2E\mathbf{I}_0}{4T_0^3}\sin^2\psi(4 - 6\sin^2\psi)\Big] \end{aligned}\right\} \quad . \quad (17)$$

Or, putting $T_0/w_0 = c$; $T_0/EQ = \lambda$; $w_0^2E\mathbf{I}_0/T_0^3 = \gamma$; we obtain :—

$$\left.\begin{aligned} x &= c\Big[gd^{-1}\psi + \lambda\tan\psi \\ &\qquad + \frac{\gamma}{4}\{\psi + \sin 2\psi(\tfrac{7}{2} - 3\sin^2\psi)\}\Big] \\ y &= c\Big[\sec\psi + \tfrac{1}{2}\lambda\tan^2\psi \\ &\qquad + \frac{\gamma}{4}\sin^2\psi(4 - 6\sin^2\psi)\Big] \end{aligned}\right\} \quad . \quad (17a)$$

It is more convenient to use these equations than those obtained by eliminating $\psi$, which is a very complicated operation.* It is interesting to note in Equations (17$a$) that the first terms on the right-hand side correspond to a non-elastic catenary; if to these be added the second terms we get the equation to an elastic catenary,† and the three terms together represent the elastic and rigid catenary at present under review.

It is clear that all the above formulæ are applicable to both wires and cables.

### III. Practical Formulæ for Dip, Tension, Length, and Temperature Effect.

($a$) *Dip.*—Let $S$ = span, i.e. the distance between A and B (see Fig. 1) ;
$D$ = dip of the suspended wire ; and
$\Psi$ = value of $\psi$ at the suspension points.

Then from Equation (17$a$) we get :—

$$\left.\begin{aligned} S &= 2c\Big[gd^{-1}\Psi + \lambda\tan\Psi \\ &\qquad + \frac{\gamma}{4}\{\Psi + \sin 2\Psi(\tfrac{7}{2} - 3\sin^2\Psi)\}\Big] \\ D &= c\Big[\sec\Psi - 1 + \tfrac{1}{2}\lambda\tan^2\Psi \\ &\qquad + \frac{\gamma}{4}\sin^2\Psi(4 - 6\sin^2\Psi)\Big] \end{aligned}\right\} \quad . \quad (18)$$

---

* The equation of an extensive string on a smooth curve is given in the following form by Dr. G. M. Minchin :—

$$y = u - \frac{v^2}{2a} + \frac{uv^2}{2a^2}$$

where $u = c\cosh(x/c)$; $v = c\sinh(x/c)$; and $a = EQ/w$.

See p. 385, vol. 1, of his "Treatise on Statics."

† J. McMahon : "Hyperbolic Functions," p. 51.

Expanding the triogonometric and gudermanian functions into potential series, and neglecting terms higher than the third order of $\Psi$, we get :—

$$S = 2c[(1 + \lambda + 2\gamma) + \tfrac{1}{6}(1 + 2\lambda - 16\gamma)\Psi^2]\Psi \quad . \quad (19)$$

$$D = \frac{c}{2}[1 + \lambda + 2\gamma]\Psi^2 \quad . \quad . \quad . \quad . \quad (20)$$

As the values of $\lambda$ and $\gamma$ are both so small compared with unity that we can neglect their second and higher powers and their products, we obtain from Equations (19) and (20) :—

$$\Psi = \frac{S}{2c(1 + \lambda + 2\gamma) + \frac{2}{3}(1 + \lambda - 18\gamma)D} \quad . \quad (21)$$

From Equations (20) and (21) we get :—

$$D = \frac{S^2}{8c(1 + \lambda + 2\gamma)\left[1 + \dfrac{D}{3c} \times \dfrac{(1 + \lambda - 18\gamma)}{(1 + \lambda + 2\gamma)}\right]^2} \quad (22)$$

or, neglecting the second power of $D/c$,

$$D = \frac{S^2}{8c}(1 - \lambda - 2\gamma)\left[1 - \frac{2D}{3c}(1 - 20\gamma)\right]$$

or
$$D \doteqdot \frac{S^2}{8c}(1 - \lambda - 2\gamma)$$

We have therefore :—

$$D = \frac{S^2}{8c}(1 - \lambda - 2\gamma) - \frac{2}{3c}(1 - 20\gamma)\left[\frac{S^2}{8c}(1 - \lambda - 2\gamma)\right]^2$$
$$= \frac{S^2}{8c}(1 - \lambda - 2\gamma) - \frac{S^4}{96c^3}(1 - 2\lambda - 24\gamma)\ ^* \quad . \quad (22a)$$

(*b*) *Tension.*—The value of $T_0$ for a given dip will be expressed in terms relating to span and size of wire by substituting $c = T_0/w_0$, $\lambda = T_0/EQ$ and $\gamma = w_0^2 E\mathbf{I}_0/T_0^3$ in Equation (22*a*), but the equation will be so complicated as to give $T_0$ in terms of the sixth order.

For practical purposes it will be more convenient to express it in the following form of Equation (22) :—

$$T_0 = \frac{w_0 S^2}{8D(1 + \lambda + 2\gamma)\left[1 + \dfrac{2D}{3c}(1 - 20\gamma)\right]}$$
$$= \frac{w_0 S^2}{8D}\left[1 - \lambda - 2\gamma - \frac{D}{3c}(1 - 20\gamma)\right] \quad . \quad (23)$$
$$= \frac{w_0 S^2}{8D}\eta\ ^\dagger \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23a)$$

in which $c$, $\lambda$, $\gamma$ and $\eta$ are all the functions of $T_0$, but $\eta$ is so near to unity that we may determine the approximate value of $T_0$ for a given span and dip by putting $T_0 = w_0 S^2/(8D)$ as a preliminary assumption, and accordingly the value of $\eta$ and consequently the correct value of $T_0$ will be obtained.

The tension at any point of the cable is shown in terms of $\psi$ as follows :—

$$T = T_0 \sec\psi - E\mathbf{I}\frac{d^2\psi}{ds^2}\tan\psi \text{ [from Eqn. (6)], and}$$

$$\frac{d^2\psi}{ds^2} = -\frac{w_0^2}{T_0^2}\sin 2\psi \cos^2\psi \text{ [from Eqns. (11}a\text{) and (13)]}$$

Assuming $\mathbf{I} = \mathbf{I}_0$, we get :—

$$T = T_0 \sec\psi + \frac{w_0^2 E\mathbf{I}_0}{2T_0^2}\sin^2 2\psi$$
$$= T_0\left(\sec\psi + \frac{\gamma}{2}\sin^2 2\psi\right) \quad . \quad . \quad . \quad (24)$$

By putting $\psi = \Psi$ and expanding the trigonometric functions in the above equation, the maximum tension $T_m$ with respect to the minimum value $T_0$ at the lowest point will be as follows :—

$$T_m = [1 + \tfrac{1}{2}(1 + 4\gamma)\Psi^2]T_0$$
$$= \left[1 + \frac{D}{c}(1 + 3\lambda - 2\gamma)\right]T_0 \quad . \quad . \quad (25)$$
$$= \eta_m T_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25a)$$

Now the criterion of the importance of flexural rigidity may be determined as follows :—

Let $S'$ = span for an elastic catenary,
$\epsilon$ = percentage error caused by neglecting flexural rigidity in calculating the span for an elastic catenary.

Then
$$S' = 2c[gd^{-1}\Psi + \lambda \tan\Psi]$$
$$= 2c[1 + \lambda + \tfrac{1}{6}(1 + 2\lambda)\Psi^2]\Psi$$

and
$$\epsilon = 100\frac{S - S'}{S} = 100\frac{4c\gamma}{S}[1 - \tfrac{4}{3}\Psi^2]\Psi$$

Substituting the corresponding values given in Equations (20), (21) and (23*a*) we get :—

$$\epsilon = 100 \times 2\gamma\left[1 - \lambda - 2\gamma - \frac{3D}{c}(1 - 20\gamma)\right] \doteqdot 100 \times 2\gamma$$

$$\doteqdot 100\frac{Ed^2D^3}{\rho(S/2)^6} \text{ per cent} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

where $d$ = diameter of the wire,
$\rho$ = volume density of the wire.

(*c*) *Length.*—Let $l$ = length of the wire stretched between A and B,
$l_0$ = ditto unstretched, i.e. with the tension released,
$s_0$ = unstretched length of $s$, with the tension released.

From Equation (13) we get, as in the dip calculation :—

$$l = 2c\tan\Psi + c\lambda[\sec\Psi \tan\Psi + gd^{-1}\Psi]$$
$$+ 2c\gamma \sin 2\Psi \cos\Psi \quad . \quad (27)$$
$$= 2c[(1 + \lambda + 2\gamma) + \tfrac{1}{6}(2 + 3\lambda - 14\gamma)\Psi^2]\Psi \quad . \quad (27a)$$

---

[*] The ordinary dip equations are as follows :—

$$D = \frac{S^2}{8c} \text{ (for a parabola)}$$
$$D = \frac{S^2}{8c}\left[1 + \frac{1}{48}\frac{S^2}{c^2} + \ldots\right] \text{ (for a catenary)}$$
$$D = \frac{S^2}{8c'}(1 - \lambda') + \frac{4}{3c'}\left[\frac{S^2}{8c'}(1 - \lambda')\right]^2 \text{(for an elastic catenary)}$$

where $c'$ and $\lambda'$ represent the corresponding values of $c$ and $\lambda$, assuming the maximum tension at the supporting points. See S. Noda, *loc. cit.*

[†] The relation $T_0 = wS^2/8D$ holds in the case of a parabolic curve.

From Equations (19) and (27$a$) we get :—

$$l = S + 2c[\tfrac{1}{6}(1 + \lambda + 2\gamma)\Psi^2]\Psi$$

Substituting in the above equation the relation shown in Equations (20), (21) and (22) we get :—

$$l = S + \frac{2D}{3}\frac{S}{2c(1 + \lambda + 2\gamma)\left[1 + \frac{D}{3c}(1 - 20\gamma)\right]}$$

$$= S + \frac{8D^2}{3S}\left[1 + \frac{D}{3c}(1 - 20\gamma)\right] \quad . \quad . \quad . \quad . \quad (28)$$

$$= S + \frac{8D^2}{3S} + \frac{8D^3}{9cS}(1 - 20\gamma)\ {}^{*} \quad . \quad . \quad . \quad . \quad (28a)$$

Inserting the relation $ds_0 = \dfrac{ds}{1 + T/EQ}$ in Equation (7) we get :—

$$ds_0 = d\left(\frac{T}{w_0}\sin\psi\right) - \frac{E\mathbf{I}}{w_0}d\left(\cos\psi\frac{d^2\psi}{ds^2}\right)$$

Integrating the above, assuming that $\mathbf{I} = \mathbf{I}_0$ and substituting the relation shown in Equation (6) for $T$, we have :—

$$s_0 = \frac{T_0}{w_0}\tan\psi - \frac{E\mathbf{I}_0}{w_0}\sec\psi\frac{d^2\psi}{ds^2}$$

$$= \frac{T_0}{w_0}\tan\psi + \frac{w_0E\mathbf{I}_0}{T_0^2}\sin 2\psi\cos\psi \quad . \quad (29)$$

Putting $\psi = \Psi$ in the above equation, from Equation (27) we obtain :—

$$l_0 = 2c[\tan\Psi + \gamma\sin 2\Psi\cos\Psi]$$

$$= l - c\lambda[\sec\Psi\tan\Psi + gd^{-1}\Psi] \quad . \quad . \quad (29a)$$

Expanding and neglecting terms higher than the third order, this becomes :—

$$l_0 = l - c\lambda(2 + \Psi^2)\Psi$$

or, substituting the relations shown in Equations (20), (21) and (22),

$$l_0 = l - \frac{8c\lambda D}{S}\left[1 + \frac{D}{c(1+\lambda+2\gamma)}\right]\left[1 + \frac{D}{3c}(1 - 20\gamma)\right] \quad . \quad (30)$$

$$\fallingdotseq l - \frac{8\lambda D}{S}[c + \tfrac{4}{3}D] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30a)$$

or, from Equations (28) and (30) :—

$$l_0 = S + \frac{8D}{S}\left[\frac{D}{3} - c\lambda - D\lambda(1 - \lambda - 2\gamma)\right]$$

$$\left[1 + \frac{D}{3c}(1 - 20\gamma)\right] \quad . \quad (31)$$

$$\fallingdotseq S + \frac{8D^2}{3S}\left[1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right] \quad . \quad . \quad . \quad . \quad (31a)$$

From Equations (31) and (31$a$) it may clearly be seen that when the condition

$$\frac{D}{3} - c\lambda - D\lambda(1 - \lambda - 2\gamma) = 0$$

or

$$D = \frac{3c\lambda}{1 - 3\lambda(1 - \lambda - 2\gamma)} \quad . \quad . \quad . \quad (32)$$

$$\fallingdotseq 3c\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (32a)$$

is satisfied, the unstretched length $l_0$ becomes equal to the span, $S$.

Also, when $\dfrac{D}{3} - c\lambda - D\lambda(1 - \lambda - 2\gamma) < 0$

or

$$D < \frac{3c\lambda}{1 - 3\lambda(1 - \lambda - 2\gamma)} \quad . \quad . \quad . \quad (33)$$

$$< 3c\lambda \text{ (approximately)} \quad . \quad . \quad (33a)$$

$l_0$ becomes less than $S$.

($d$) *Temperature effect.*—Let $T_0$ = minimum tension of the wire at the datum temperature,

$D$ = dip at the datum temperature,

$T_0'$ = minimum tension of the wire at a higher temperature,

$D'$ = dip at a higher temperature,

$t$ = temperature-difference between the tensions $T_0$ and $T_0'$,

$\alpha$ = temperature coefficient of linear expansion of the wire,

$l_0'$ = unstretched length of the wire at a temperature-difference $t$,

$c', \lambda', \gamma', \eta'$ = values corresponding to $c, \lambda, \gamma, \eta$ at a temperature-difference $t$.

Then $l_0' = l_0(1 + \alpha t)$

$$= \left[S + \frac{8D}{S}\left\{\frac{D}{3} - c\lambda - D\lambda(1 - \lambda - 2\gamma)\right\}\right.$$

$$\left.\left\{1 + \frac{D}{3c}(1 - 20\gamma)\right\}\right](1 + \alpha t)$$

$$\fallingdotseq S\left[1 + \frac{8D^2}{3S^2}\left\{1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right\}\right](1 + \alpha t)$$

$$\fallingdotseq S\left[1 + \alpha t + \frac{8D^2}{3S^2}\left\{1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right\}\right] \quad . \quad (34)$$

Taking $w_0/(1 + \alpha t)$ and $\mathbf{I}_0(1 + \alpha t)^4$ instead of $w_0$ and $\mathbf{I}_0$ respectively, we have :—

$$\left.\begin{aligned} c' &= \frac{T_0'}{w_0}(1 + \alpha t) \\ \lambda' &= \frac{T_0'}{EQ\,(1 + \alpha t)^2} \\ \gamma' &= \frac{w_0^2E\mathbf{I}_0}{T_0'^3}(1 + \alpha t)^2 \\ T_0' &= \frac{w_0S^2}{8D'(1+\alpha t)}\left[1 - \lambda' - 2\gamma' - \frac{2D'}{3c'}(1 - 20\gamma')\right] \\ &= \frac{w\,S^2\eta'}{8D'(1 + \alpha t)} \end{aligned}\right\} \quad (35)$$

---

* The usual approximate formulæ for $l$ are as follows :—

$$l = S + \frac{8D^2}{3S} \text{ (for a catenary)}$$

$$= S + \frac{8D^2}{3S} - \frac{16D^3}{9c'S} \text{ (for an elastic catenary)}$$

At a temperature-difference $t$, the unstretched length, $l_0'$, of the wire takes the following form [from Equation (31$a$)]:—

$$l_0' = S + \frac{8D'^2}{3S}\left[1 - 3\lambda'\left(\frac{c'}{D'} + 1\right) + \frac{D'}{3c'}\right] \quad . \ (36)$$

Therefore from Equations (34) and (36) we have the following:—

$$S + \frac{8D'^2}{3S}\left[1 - 3\lambda'\left(\frac{c'}{D'} + 1\right) + \frac{D'}{3c'}\right]$$
$$= S\left[1 + at + \frac{8D^2}{3S^2}\left\{1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right\}\right]$$

Substituting the relations shown in Equations (35) and rearranging, we obtain:—

$$\frac{8D'^5}{3S^2\eta'} + D'^3 - \frac{3w_0S^2D'^2\eta'}{8EQ(1 + at)^3}$$
$$- \frac{3S^2}{8}\left[at + \frac{8D^2}{3S^2}\left\{1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right\}\right]D'$$
$$- \frac{3w_0S^4\eta'^2}{64EQ(1 + at)^3} = 0 \quad . \ . \ . \ . \ . \ . \ (37)$$

from which the dip at any temperature-difference $t$ can be computed if the material and size of wire, span and dip at the datum temperature are known.

In Equation (37), however, the coefficients of $D'^5$ and $D'^2$ are both so small compared with the others in the case of ordinary spans (say 200–500 ft.) that we may neglect those terms and write the formula in the form:—

$$D'^3 - \frac{3S^2}{8}\left[at + \frac{8D^2}{3S^2}\left\{1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right\}\right]D'$$
$$- \frac{3w_0S^4\eta'^2}{64EQ(1 + at)^3} = 0 \quad . \ (38)$$

The value of $\eta'$ approaches unity and its influence on the value of $D'$ is negligibly small in the majority of cases.

### III. NUMERICAL EXAMPLES.

In order to give a clear idea of the effects of elasticity and rigidity on cable span calculations, some numerical data are shown in the table on page 1085, compiled from information supplied by Mr. E. Parry, Chief Engineer to the English Electric Company, Limited.

Take the case of copper wire of No. 4/0 S.W.G. suspended with a minimum tension of 8 500 lb. per sq. in. on a span of 500 ft. in still air.

Diameter of conductor = 0·4 inch.

$E = 18 \times 10^6$ lb. per sq. in.

$Q = 0{\cdot}1257$ sq. in.; $w_0 = 0{\cdot}485$ lb. per ft.

$T_0 = 1\,068$ lb.; $c = T_0/w_0 = 2\,200$ ft.

$\lambda = T_0/EQ = 4{\cdot}72 \times 10^{-4}$.

$$\gamma = \frac{w_0^2EI_0}{T_0^3} = \frac{0{\cdot}485^2 \times 18 \times 10^6 \times (\pi/64) \times 0{\cdot}4^4}{1\,068^3 \times 12^2}$$
$$= 3{\cdot}03 \times 10^{-8}$$

$$D = \frac{S^2}{8c}(1 - \lambda - 2\gamma) - \frac{S^4}{96c^3}(1 - 2\lambda - 24\gamma)$$
$$= \frac{500^2}{8 \times 2\,200} \times 0{\cdot}9995 - \frac{500^4}{96 \times 2\,200^3} \times 0{\cdot}9990$$
$$= 14{\cdot}14 \text{ feet}$$

$$T_m = \left[1 + \frac{D}{c}(1 + 3\lambda - 2\gamma)\right]T_0 = 1{\cdot}0064T_0$$

$$l \doteq S + \frac{8D^2}{3S} + \frac{8D^3}{9cS}(1 - 20\gamma)$$
$$= 500 + \frac{8 \times 14{\cdot}14^2}{3 \times 500} + \frac{8 \times 14{\cdot}14^3}{9 \times 2\,200 \times 500} \times (1 - 20 \times 3{\cdot}03 \times 10^{-8})$$
$$= 501{\cdot}07 \text{ feet}$$

$$l_0 = S + \frac{8D^2}{3S}\left[1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right]$$
$$= 500 + \frac{8 \times 14{\cdot}14^2}{3 \times 500}\left[1 - 3 \times 4{\cdot}72 \times 10^{-4} \times \frac{2\,200 + 14{\cdot}14}{14{\cdot}14} + \frac{14{\cdot}14}{3 \times 2\,200}\right]$$
$$= 500 + 1{\cdot}067 \times 0{\cdot}78$$
$$= 500{\cdot}83 \text{ feet}$$

$$3c\lambda = 3 \times 2\,200 \times 4{\cdot}72 \times 10^{-4} = 3{\cdot}12 \text{ feet} < D = 14{\cdot}14$$

which proves that the unstretched length of the wire is a little longer than the span.

Now the dip at a temperature 50 degrees F. lower than the temperature assumed in the previous calculation may be obtained as follows:—

$$\frac{3S^2}{8}\left[at + \frac{8D^2}{3S^2}\left\{1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right\}\right]$$
$$= \frac{3 \times 500^2}{8} \times (-\,0{\cdot}000473 + 0{\cdot}001664)$$
$$= 111{\cdot}6$$

also $$\frac{3w_0S^4\eta'^2}{64EQ(1 + at)^3} = 628$$

therefore $D'^3 - 111{\cdot}6D' - 628 = 0$ (assuming $\eta' = 1$)

whence $D' = 12{\cdot}7$ feet

$$T_0' = \frac{w_0S^2\eta'}{8D'(1 + at)}$$
$$= \frac{0{\cdot}485 \times 500^2 \times 1}{8 \times 12{\cdot}7 \times 0{\cdot}9995}$$
$$= 1\,194 \text{ lb.}$$

The tension per unit sectional area at the lowest point is 9 500 lb. per sq. in.

also $\lambda' = 5{\cdot}28 \times 10^{-4}$; $\gamma' = 2{\cdot}17 \times 10^{-8}$

$c' = 2\,460$ ft.; $\dfrac{2D'}{3c'} = 3{\cdot}44 \times 10^{-3}$

therefore

$$\eta' = \left[1 - \lambda' - 2\gamma' - \frac{2D'}{3c'}(1 - 20\gamma')\right] = 0{\cdot}9960$$

which clearly shows that the error caused by assuming $\eta' = 1$ is negligibly small.

PROPERTIES OF MATERIALS IN GENERAL USE FOR SPANS.

| Materials | Copper | | Aluminium | | High-carbon steel | | Steel-cored aluminium cable | | Low-carbon steel cable | Iron wire |
|---|---|---|---|---|---|---|---|---|---|---|
| | Wire | Cable | Wire | Cable | Wire | Cable | 7-strand | 37-strand | | |
| Modulus of elasticity, $E$, lb./sq. in. | $18 \times 10^6$ | $18 \times 10^6$ | $10 \times 10^6$ | $10 \times 10^6$ | $30 \times 10^6$ | $30 \times 10^6$ | $12\cdot 85 \times 10^6$ | $13\cdot 8 \times 10^6$ | $30 \times 10^6$ | $26 \times 10^6$ |
| Tensile strength, lb./sq. in. .. | 54 000 | 50 000 | 26 000 | 24 000 | 180 000 | 166 000 | 43 000 | 49 000 | 56 000 | 56 000 |
| Elastic limit, lb./sq. in. .. | 27 000 | 25 000 | 13 000 | 12 000 | 130 000 | 120 000 | 30 600 | 36 000 | 34 000 | 22 500 |
| Specific gravity, rolled or drawn | 8·90 | — | 2·71 | — | 7·74 | — | — | — | 7·74 | 7·8 |
| Weight in lb. per foot per sq. in. section .. | 3·85 | 3·93 | 1·172 | 1·195 | 3·36 | 3·43 | 1·51 | 1·62 | 3·43 | — |
| Coefficient of linear expansion $\alpha$, per degree F. .. | $9\cdot 45 \times 10^{-6}$ | $9\cdot 45 \times 10^{-6}$ | $13\cdot 3 \times 10^{-6}$ | $13\cdot 3 \times 10^{-6}$ | $6\cdot 4 \times 10^{-6}$ | $6\cdot 4 \times 10^{-6}$ | $11\cdot 0 \times 10^{-6}$ | $10\cdot 48 \times 10^{-6}$ | $6\cdot 8 \times 10^{-6}$ | $6\cdot 8 \times 10^{-6}$ |

If this wire be suspended under a tension of 15 000 lb. per sq. in., we have :—

$$T_0 = 1\,886 \text{ lb.}\,; \quad c = 3\,890 \text{ ft.}\,; \quad \lambda = 8\cdot 33 \times 10^{-4}\,;$$
$$\gamma = 0\cdot 55 \times 10^{-8}; \quad D = 8\cdot 03 \text{ ft.},$$

and $\qquad 3c\lambda = 9\cdot 72 \text{ ft.} > D = 8\cdot 03 \text{ ft.}$

which proves that the unstretched length of the wire is shorter than the span.

In the present cases, it will be seen that the effect of shearing stress need not be taken into account.

But if we take a copper wire 1 inch in diameter suspended at the lowest tension of 1 500 lb. per sq. in. we have :—

$$Q = 0\cdot 7854 \text{ sq. in.}\,; \qquad w_0 = 3\cdot 02 \text{ lb.}$$
$$T_0 = 1\,177 \text{ lb.}\,; \qquad c = 390 \text{ ft.}$$
$$\lambda = 0\cdot 833 \times 10^{-4}\,; \qquad \gamma = 0\cdot 343 \times 10^{-4}$$
$$D = 69\cdot 2 \text{ ft. at } 500 \text{ ft. span}$$

and at the lowest tension of 1 000 lb. per sq. in.,

$$T_0 = 785\cdot 4 \text{ lb.}\,; \qquad c = 260 \text{ ft.}$$
$$\lambda = 0\cdot 556 \times 10^{-4}\,; \qquad \gamma = 1\cdot 16 \times 10^{-4}$$
$$D = 83\cdot 1 \text{ ft. at } 500 \text{ ft. span.}$$

It will be seen that when the tension is reduced the coefficient $\gamma$, which modifies the form of a suspended cable due to the shearing, becomes more important than the coefficient $\lambda$ due to the elasticity, and that it increases rapidly with the diameter.

Let us now consider a case where a solid copper conductor (say 100 yards long) is hung under tension and supported at points, say, 7 ft. apart, e.g. a trolly wire for an electric railway. It would appear as though the elastic equations should be used to investigate this case, but it is an exceptional case and brings to light a new fact which makes the elastic equation superfluous. If we allow a dip of 0·03 ft. between supports for No. 4/0 S.W.G. copper wire, we have $\lambda = 4\cdot 36 \times 10^{-5}$ and $\epsilon = 7\cdot 6 \times 10^{-3}$ per cent. The inclination of the centre line of the wire to the horizontal is always very small, so that the accurate differential equations at once break down into very simple forms, which can be handled by means of ordinary hyperbolic sines and cosines.

The shearing strength of copper is about 0·83 times the tensile strength. In the case of No. 4/0 S.W.G. and a span of 500 ft., the shearing stress at the point of suspension is only $0\cdot 485 \times 250 \times (1/0\cdot 1257) = 965$ lb. per sq. in., and in the case of 1 inch diameter and 500 ft. span it is also $3\cdot 02 \times 250 \times (1/0\cdot 7854) = 965$ lb. per sq. in., which is far below the shearing strength. There will, therefore, be no likelihood of the cable breaking down on account of shearing stress due to its own weight at the customary cable spans.

## IV. CONCLUSION.

(1) The form of a suspended cable, taking into account elasticity and rigidity, is shown by the following formulæ :—

$$s = c[\tan\psi + \tfrac{1}{2}\lambda(\sec\psi\tan\psi + gd^{-1}\psi) + \gamma\sin 2\psi\cos\psi)] \quad . \quad (13)$$

$$\left.\begin{aligned} x &= c\Big[gd^{-1}\psi + \lambda\tan\psi + \frac{\gamma}{4}\Big\{\psi + \sin 2\psi(\tfrac{7}{2} - 3\sin^2\psi)\Big\}\Big] \\ y &= c\Big[\sec\psi + \tfrac{1}{2}\lambda\tan^2\psi + \frac{\gamma}{4}\sin^2\psi(4 - 6\sin^2\psi)\Big] \end{aligned}\right\} \quad . \quad (17a)$$

where $c = T_0/w_0$, $\lambda = T_0/EQ$, $\gamma = w_0^2 E\mathrm{I}_0/T_0^3$.

(2) The tension at any point of the cable is given by the following formula in terms of the lowest tension :—

$$T = [\sec\psi + \tfrac{1}{2}\gamma\sin^2 2\psi]T_0 \quad . \quad . \quad . \quad (24)$$

(3) The following are the practical formulæ for span calculations :—

$$D = \frac{S^2}{8c}(1 - \lambda - 2\gamma) - \frac{S^4}{96c^3}(1 - 2\lambda - 24\gamma) \quad . \quad . \quad (22a)$$

$$T_0 = \frac{w_0 S^2}{8D}\left[1 - \lambda - 2\gamma - \frac{2D}{3c}(1 - 20\gamma)\right]. \quad . \quad . \quad (23)$$

$$T_m = \left[1 + \frac{D}{c}(1 + 3\lambda - 2\gamma)\right]T_0 \quad . \quad . \quad . \quad . \quad . \quad (25)$$

$$l = S + \frac{8D^2}{3S} + \frac{8D^3}{9cS}(1 - 20\gamma) \quad . \quad . \quad . \quad . \quad . \quad (28a)$$

$$l_0 = l - \frac{8\lambda D}{S}\left(c + \frac{4}{3}D\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30a)$$

$$= S + \frac{8D^2}{3S}\left[1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right] \quad . \quad . \quad . \quad . \quad (31a)$$

$$l_0' = S\left[1 + at + \frac{8D^2}{3S^2}\left\{1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right\}\right] \quad . \quad (34)$$

$$D'^3 - \frac{3S^2}{8}\left[at + \frac{8D^2}{3S^2}\left\{1 - 3\lambda\frac{c + D}{D} + \frac{D}{3c}\right\}\right]D' - \frac{3w_0 S^4\eta'^2}{64EQ(1 + at)^3} = 0 \quad . \quad (38)$$

(4) If elasticity is taken into account, the unstretched span of cable is shorter than a given span when the following condition obtains :—

$$D < 3c\lambda = \frac{3T_0^2}{w_0 EQ} \quad . \quad . \quad . \quad . \quad (33a)$$

(5) The effect of shearing stress increases rapidly with $\psi$ and the diameter of a cable.

(6) For the purpose of span calculations in such a case as an electric transmission line suspended at a greater tension, there is no need to consider the effect of shearing stress. With the lower tension, however, the effect of shearing stress increases rapidly and becomes more important than the effect due to elasticity. This is quite evident, since, when $T_0$ is zero, the cable, if it supports itself at all, will do so entirely by flexural rigidity.

(7) The criterion of the importance of flexural rigidity can be written :—

$$\epsilon = 100 \times 2\gamma = 100\frac{E}{\rho}\times\frac{d^2D^3}{S_s^6} \text{ per cent} \quad . \quad (26)$$

where $\epsilon$ is the percentage error due to the neglect of flexural rigidity in calculating the span by the usual formula. In this formula $S_s$ is the semi-span. When $\lambda < 2\gamma$, the effect of flexural rigidity is more important than that of elasticity.

(8) For light materials, e.g. an aluminium cable, the effect of shearing stress is less for a given tension, because $\gamma$ is proportional to the square of $w_0$. For a given dip it becomes greater, because $\epsilon$ is inversely proportional to $\rho$.

For materials capable of being suspended under greater tension, e.g. a steel cable, the effect of shearing stress is smaller, because $\gamma$ is inversely proportional to the cube of $T_0$.

(9) The maximum shearing stress at the suspended point, due to the weight of the wire, is far less than the shearing strength under normal span conditions ; at the same time it is desirable that both ends of the hanger of the suspended cable should be bent downwards by an angle $\Psi$ in order to avoid sharp bends at the suspended point.

(10) The effect of shearing stress should be considered in a case where the supporting points are not on an horizontal level, for the value of $\psi$ on one side is increased according to the difference of level.

In conclusion, the author desires to express his thanks to Dr. S. Noda and Mr. E. Parry for their valuable suggestions in regard to the paper.

# THE NATURE OF THE MAGNETIC FIELD PRODUCED BY THE STATOR OF A THREE-PHASE INDUCTION MOTOR, WITH SPECIAL REFERENCE TO POLE-CHANGING MOTORS.*

By F. J. TEAGO, Member.

(*Paper first received 4th April, and in final form 29th May*, 1923.)

### SUMMARY.

In dealing with the subject of stator and rotor windings it has been usual to describe a coil in terms of its slot pitch, that is, in terms of the number of slots spanned by the coil.

The author feels that a certain amount of confusion arises when it is attempted to describe windings in terms of "pitch," and it is proposed to use the terms "Normal Distribution" and "Super-Distribution" which are definite and lend themselves to very simple mathematical representation.

A case of normal distribution of the winding is one in which the windings of one phase are put into a number of consecutive slots per pole equal to the actual number of stator slots per pole per phase, and where no other phase windings are interleaved with them.

It is hoped that this innovation will prove useful and convenient.

It is shown that with one coil-side per slot there is little benefit to be derived from a departure from a normal distribution of the winding, but that with two coil-sides per slot super-distribution is useful.

In Table 6 it is shown how, by means of simple mathematical expressions, to decide upon the style of winding most likely to suppress a tendency to "crawl" in any given case.

The changes in the flux density and magnetizing current, with changes in the number of poles, are discussed, together with their bearing upon the phenomenon of crawling.

The influence of the type of slot employed and its proximity to the bore is also examined.

---

### SYNOPSIS OF CONTENTS.

Introduction.
I. The nature of the magnetic field produced by the stator of an induction motor when wound with symmetrical coils of normal distribution.
II. The effect of symmetrical super-distributed coils, using one coil-side per slot.
III. The effect of symmetrical super-distributed coils, using two coil-sides per slot.
IV. Symmetrical coils with and without initial super-distribution in pole-changing motors.
V. The changes in the magnetizing current.
VI. The effect of saturation in the iron parts of the circuit.

### INTRODUCTION.

In this paper it is assumed that the motor is unloaded and that, during the preliminary stages, there is no saturation in the iron parts. The effect of saturation is then dealt with.

Only those cases having a whole number of slots per pole per phase are considered.

It is important to note that the harmonics in the M.M.F. curves under consideration are due to the phase windings being contained in slots, and are not due to the presence of harmonics in the wave-shape of the supply current.

If it is assumed that the wave-shape of the supply current is sinusoidal, it can be proved that, when all three phases are taken together, the resultant of the third harmonic in the M.M.F. curve is zero. This also applies to harmonics which are a multiple of the third. For this reason these harmonics are not considered here.

According to Fourier's theorem, it is possible to analyse any perfectly symmetrical periodic curve into a fundamental sine curve, together with a number of sine curves having periodicities which are odd multiples of the fundamental periodicity.

## I. THE M.M.F. CURVE PRODUCED BY THE STATOR OF AN INDUCTION MOTOR WITH SYMMETRICAL COILS OF NORMAL DISTRIBUTION.

Considering any one phase of a three-phase winding where the turns are concentrated in one unskewed slot per pole per phase, the space distribution of the M.M.F. curve over one pole-pitch, at the instant when the current is a maximum, is as shown in Fig. 1.

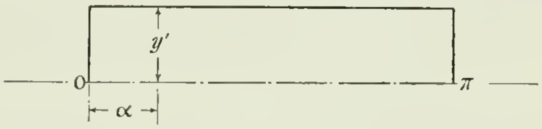


FIG. 1.

In Fig. 1 let $A_n$ = maximum amplitude of the $n$th sine harmonic,

$\lambda$ = distance over two pole-pitches,

$x$ = distance of any point from the origin,

$y'$ = height of the curve at that point,

$y$ = maximum height of the curve,

$a = 2\pi x/\lambda$

then
$$A_n = \frac{4}{\pi}\int_0^{\pi/2} y' \sin na \,.\, da$$

In this case $y'$ is constant and equal to $y$, the maximum value of the ampere-turns per pole per phase, so that

$$A_n = \frac{4y}{\pi}\int_0^{\pi/2} \sin na \,.\, da$$

$$= \frac{4y}{n\pi}, \text{ for } n = \text{odd integer.}$$

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

In all cases where the turns per pole per phase are distributed in slots in such a manner that a symmetrical M.M.F. curve is produced, it is found that an expression of the form

$$A_n = \frac{4y}{n\pi} X$$

can always be obtained. In this paper $X$ is called the reduction factor, because if the maximum amplitude of any harmonic in the concentrated case is multiplied by this factor, then the maximum amplitude of the corresponding harmonic in the distributed case is obtained, though it must be distinctly understood throughout these notes that the reduction factor, by itself, does not give the amplitude of a harmonic.

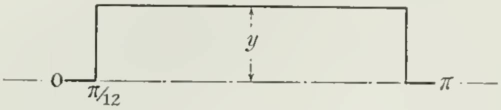


Fig. 2.

The M.M.F. curve for a winding normally distributed in two unskewed slots per pole per phase is shown in Fig. 2.

Here
$$A_n = \frac{4y}{\pi} \int_{\pi/12}^{\pi/2} \sin na \,.\, da$$
$$= \frac{4y}{n\pi} \cos \frac{n\pi}{12}$$

The M.M.F. curve for a winding normally distributed in an infinite number of unskewed slots per pole per phase is shown in Fig. 3.

Here
$$A_n = \frac{4y}{\pi} \left[ \frac{6}{\pi} \int_0^{\pi/6} a \sin na \,.\, da + \int_{\pi/6}^{\pi/2} \sin na \,.\, da \right]$$
$$= \frac{4y}{n\pi} \times \frac{6}{n\pi} \sin \frac{n\pi}{6}$$

In a similar manner expressions can be obtained for any given integral number of unskewed slots per pole per phase. A few reduction factors for three-phase windings with coils normally distributed are set out in Table 1.

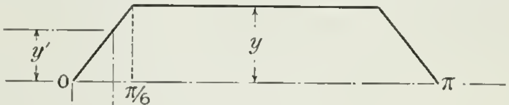


Fig. 3.

It will be noticed that these expressions are of definite formation and bear a common likeness, and if they are put into the form

$$\cos A + \cos (A + B) + \cos (A + 2B) + \ldots \text{ to } r \text{ terms}$$
$$= \frac{\cos [A + \frac{1}{2}(r-1)B] \sin \frac{1}{2}rB}{\sin \frac{1}{2}B}$$

and putting $\psi$ = angle between successive slots, in electrical degrees,

$m$ = number of slots per pole per phase,

$n$ = the order of the required harmonic,

they are all represented by the expression

$$\text{reduction factor} = \frac{\sin \frac{1}{2}nm\psi}{m \sin \frac{1}{2}n\psi}$$

An expression of this form has already been used.*

The objection to a pronounced harmonic in the M.M.F. curve is its possible appearance in the flux wave. If this happens it will probably appear in the rotor current and make its presence felt in the torque characteristic of the motor.†

Table 1.

| Slots per pole per phase | Reduction factor |
|---|---|
| 1 | $1 \cdot 0$ |
| 3 | $\frac{2}{3} (0\cdot 5 + \cos n\pi/9)$ |
| 5 | $\frac{2}{5} (0\cdot 5 + \cos n\pi/15 + \cos 2n\pi/15)$ |
| 2 | $\cos n\pi/12$ |
| 4 | $\frac{1}{2} (\cos n\pi/24 + \cos 3n\pi/24)$ |
| 6 | $\frac{1}{3} (\cos n\pi/36 + \cos 3n\pi/36 + \cos 5n\pi/36)$ |
| ∞ | $\frac{6}{n\pi} (\sin n\pi/6)$ |

Evaluating the reduction factors for windings of normal distribution in unskewed slots, Table 2 is obtained.

Table 2.

| Order of harmonic | Slots per pole per phase | |
|---|---|---|
| | 2 | ∞ |
| Fundamental | 0·966 | 0·955 |
| 5th | 0·259 | 0·191 |
| 7th | −0·259 | −0·136 |
| 11th | −0·966 | −0·087 |
| 13th | −0·966 | 0·073 |

It should be noted that, although some of the reduction factors have negative values, this does not signify negative torques; the reason being that at the same instant the rotor currents are also negative.

It will be noticed that certain harmonics have a reduction factor numerically equal to that of the fundamental; this means that some values of $n$ make

$$\frac{\sin \frac{1}{2}m\psi}{m \sin \frac{1}{2}\psi} = \frac{\sin \frac{1}{2}nm\psi}{m \sin \frac{1}{2}n\psi}$$

and it is easily proved that these values are given by

$$n = 6sm \pm 1$$

where $s$ = an integral number.

---

* S. P. Smith and R. S. H. Boulding: "The Shape of the Pressure Wave in Electrical Machinery," *Journal I.E.E.*, 1915, vol. 53, p. 205.

† J. K. Catterson-Smith: "Induction Motor Design," *Journal I.E.E.*, 1912, vol. 49, p. 635.

Thus, the greater the number of slots per pole per phase, the greater is the order of the harmonic involved.

Since it is not a practical proposition to use a very large number of slots, the alternative of skewing the slots through a full slot-pitch becomes valuable. If a motor were provided with slots skewed one slot-pitch, the M.M.F. curve would become as shown in Fig. 3, for which Table 2 shows that the harmonics are practically eliminated and that no harmonic has a reduction factor equal to that of the fundamental.

### II. The Effect of Super-distributed Windings, using one Coil-side Per Slot, with Perfectly Symmetrical Windings in all Three Phases.

Fig. 4 shows one phase of a 2-pole, whole-coiled, three-phase winding, the number of slots per pole per phase being four and the distribution normal. It also shows the M.M.F. curve for the winding, together with the reduction factor.

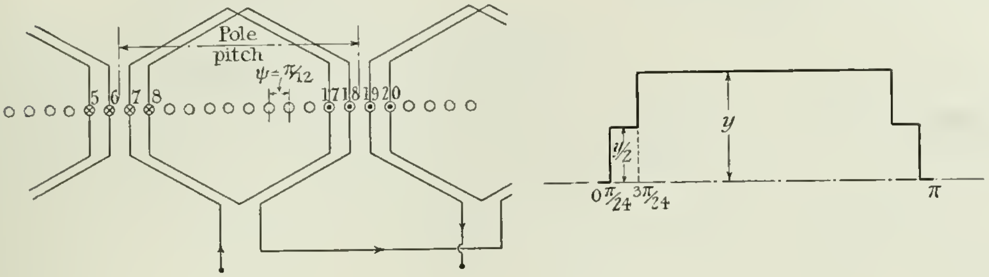
This may wrongly be regarded as a case of short pitch on account of the fact that the coil-pitch is equal to ten slots. In reality it is full pitch because the coil-sides are grouped in consecutive slots which are one pole-pitch apart. Conductor No. 7 could easily be connected to No. 19 and this scheme followed throughout.

Thus, although the "pitch" is a rather indefinite term, the winding is definitely described when referred to as "normally distributed."

Fig. 5 shows the coil-pitch of this winding reduced to nine slots; it is noticed that two slots, Nos. 6 and 9, containing conductors belonging to the other two phases, are introduced between the slots containing the conductors of the phase under consideration, and for this reason the winding is termed super-distributed.

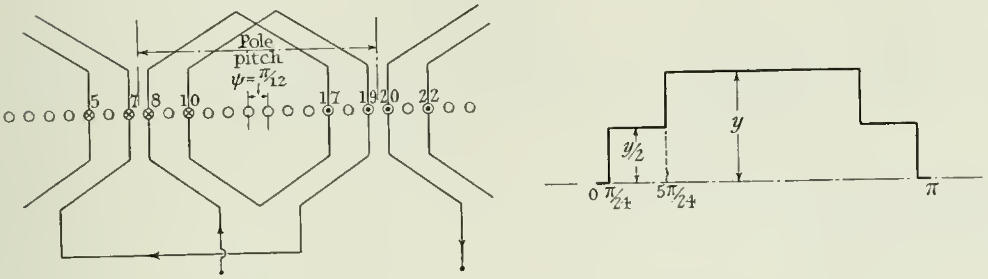
Fig. 6 shows the coil-pitch of this winding reduced to seven slots. Here it is noticed that four slots, Nos. 6, 8, 9 and 11, are introduced between the slots containing the conductors of the phase under consideration.

Style of winding — M.M.F. curve — Reduction factor $n^{th}$ harmonic



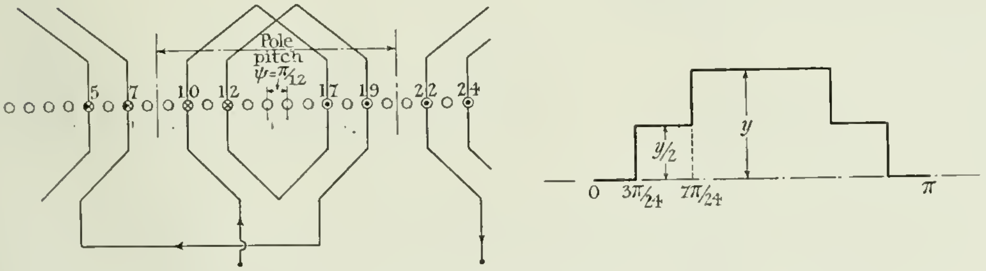
$\frac{1}{2}\left(\cos\frac{n\pi}{24}+\cos\frac{3n\pi}{24}\right)$

Fig. 4.



$\frac{1}{2}\left(\cos\frac{n\pi}{24}+\cos\frac{5n\pi}{24}\right)$

Fig. 5.



$\frac{1}{2}\left(\cos\frac{3n\pi}{24}+\cos\frac{7n\pi}{24}\right)$

Fig. 6.

Figs. 4, 5 and 6.—Two-pole whole-coiled three-phase windings; 4 unskewed slots per pole per phase; 1 coil-side per slot.

It will be noticed that the general form of the super-distributed reduction factors resembles that for the normal distribution, and they can indeed be expressed in forms similar to those given for normally distributed windings on page 1088, but the most useful form is the ratio of the super-distributed reduction factor to the normally distributed reduction factor.

An examination of Figs. 4, 5 and 6 shows that when the distribution of the winding is increased above the normal, slots containing conductors belonging to the other two phases are introduced between the slots containing the conductors of the phase under consideration.

In the case of Fig. 5, two slots, Nos. 6 and 9, are introduced between the four slots Nos. 5, 7, 8 and 10 which contain the conductors of one phase. In the case of Fig. 6, four slots, Nos. 6, 8, 9 and 11, are introduced between the four slots, Nos. 5, 7, 10 and 12, which contain the conductors of one phase.

Let $\xi$ = number of slots introduced between the group of slots containing the conductors of any one phase;

then, with unskewed slots,

$$\frac{\text{Reduction factor of } n\text{th harmonic super-distribution}}{\text{Reduction factor of } n\text{th harmonic normal distribution}} = \frac{\cos(\xi+1)\frac{1}{2}n\psi}{\cos\frac{1}{2}n\psi}$$

In those cases of one coil-side per slot where super-distribution is used the reduction factors are given by

$$\frac{\sin\frac{1}{2}nm\psi}{m\sin\frac{1}{2}n\psi} \times \frac{\cos(\xi+1)\frac{1}{2}n\psi}{\cos\frac{1}{2}n\psi}$$

Evaluating the reduction factors, for the case of four unskewed slots per pole per phase, Table 3 is obtained.

TABLE 3.

| Order of harmonic | Normal distribution | Super-distribution | |
|---|---|---|---|
| | $\xi = 0$ | $\xi = 2$ | $\xi = 4$ |
| Fundamental | 0·958 | 0·892 | 0·766 |
| 5th | 0·205 | −0·099 | −0·257 |
| 7th | −0·158 | 0·239 | 0·034 |
| 11th | −0·126 | 0·370 | −0·588 |
| 13th | 0·126 | −0·370 | 0·588 |
| 23rd | −0·958 | −0·892 | −0·766 |
| 25th | −0·958 | −0·892 | −0·766 |

It is noticed, in each case, that the harmonics which have reduction factors numerically equal to that of the fundamental are given by

$$n = 6sm \pm 1$$

where $s$ is an integral number.

Table 3 also shows that with a coil-pitch equal to nine slots, the fifth harmonic is almost zero, and with a coil-pitch of seven slots, the seventh harmonic is practically zero; but in general, both cases of super-distribution give a more undesirable M.M.F. curve than the normal case.

(NOTE.—If the numerical value of the reduction factor for the fundamental is taken to represent the maximum amplitude of the fundamental, then the maximum amplitude of the $n$th harmonic will be represented by

$$\frac{\text{Reduction factor of } n\text{th harmonic}}{n}$$

Again, with a coil-pitch equal to seven slots, owing to the reduction in the maximum height of the fundamental, the ampere-turns would have to be increased about 25 per cent over the ampere-turns required with a coil-pitch equal to ten slots, if the flux density in the air-gap is to be kept constant. (Thus it is very doubtful if any advantage is to be gained from super-distribution when using one coil-side per slot, since the object of any scheme of winding is to suppress harmonics.)

## III. THE EFFECT OF SUPER-DISTRIBUTION USING TWO COIL-SIDES PER SLOT WITH PERFECTLY SYMMETRICAL WINDINGS IN ALL THREE PHASES.

Fig. 7 shows a 2-pole, whole-coiled, three-phase winding with two unskewed slots per pole per phase. The pitch of the coils is five slots and the winding is normally distributed. The only difference between a slot-pitch of five and one of six is a difference in the end connections. The M.M.F. curves and reduction factors, for the phase shown, are exactly alike for both cases and are represented, over one pole-pitch, as indicated.

TABLE 4.

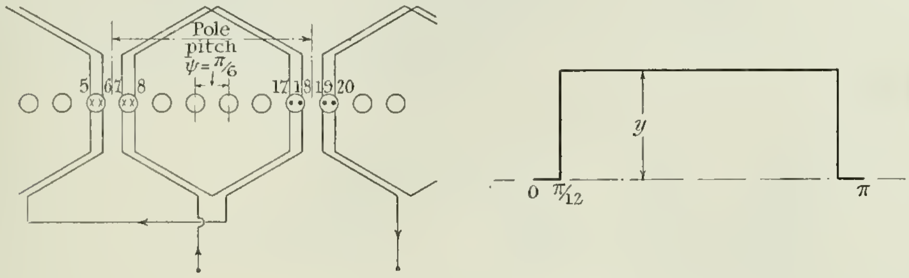
| Order of harmonic | Normal distribution | Super-distribution | |
|---|---|---|---|
| | Coil-pitch = 5, $\sigma = 0$ | Coil-pitch = 5, $\sigma = 1$ | Coil-pitch = 4, $\sigma = 2$ |
| Fundamental | 0·966 | 0·933 | 0·836 |
| 5th | 0·259 | 0·067 | −0·224 |
| 7th | −0·259 | 0·067 | 0·224 |
| 11th | −0·966 | 0·933 | −0·836 |
| 13th | −0·966 | 0·933 | −0·836 |

Fig. 8 shows quite a different arrangement for the position of the conductors, at the same time using a coil-pitch equal to five slots. Here again the term "pitch" is indefinite, since Figs. 7 and 8 both have the same coil-pitch, but their M.M.F. curves and reduction factors are not alike. However, by describing Fig. 8 as a case of super-distribution, all chances of confusion are avoided and it is observed in this case that the conductors of either phase are distributed in three slots per pole, and that the reduction factor bears a resemblance to that for the case of normally distributed coils in three slots per pole per phase (see page 1088).

Fig. 9 shows the winding set out with a coil-pitch equal to four slots; the M.M.F. curve and reduction factor are also shown.

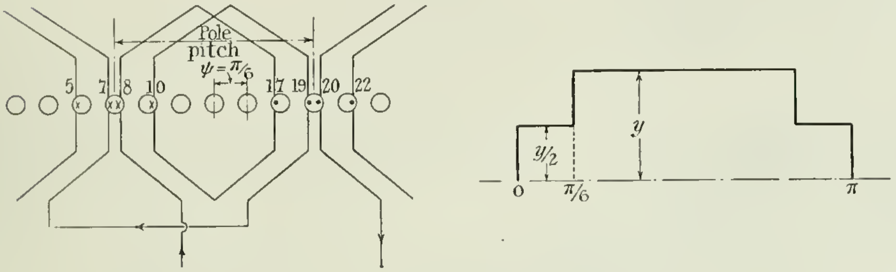
The conductors of either phase are now distributed in four slots per pole and the reduction factor resembles that for the case of normally distributed coils in 4 slots per pole per phase. (NOTE.—Further distribution can only be obtained by accepting the type obtained when one coil-side per slot is used.)

Style of winding — M.M.F. curve — Reduction factor $n^{th}$ harmonic



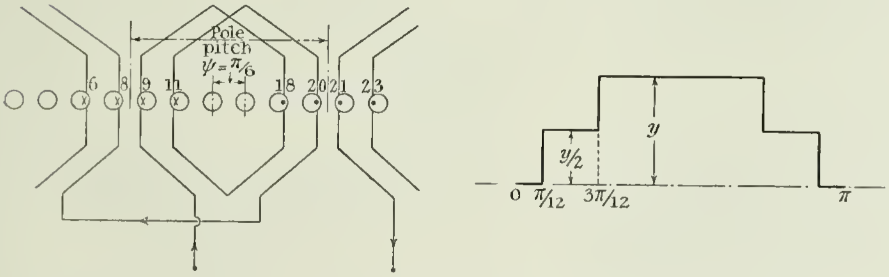
$$\cos\frac{n\pi}{12}$$

FIG. 7.



$$\frac{1}{2}\left(1+\cos\frac{n\pi}{6}\right)$$

FIG. 8.



$$\frac{1}{2}\left(\cos\frac{n\pi}{12}+\cos\frac{3n\pi}{12}\right)$$

FIG. 9.

FIGS. 7, 8 AND 9.—Two-pole whole-coiled three-phase windings; 2 unskewed slots per pole per phase; 2 coil-sides per slot.

Evaluating the reduction factors for these three cases of two unskewed slots per pole per phase with two coil-sides per slot, Table 4 is obtained.

From Table 4 it is seen that the M.M.F. curve for super-distribution with a coil-pitch of five is much better than that for the normal distribution with a slot-pitch of five, whilst the M.M.F. curve for super-distribution with a coil-pitch of four is much worse than either of the other two; this is so because, with a coil-pitch of four, the value of the fundamental is very much reduced, and the harmonics are relatively as large as they are with a normally distributed pitch of five.

With regard to the super-distribution of the windings in the above cases, it will be noticed from Table 4 that, although the conductors of any one phase lie in an increasing number of slots per pole as the coil-pitch is reduced, the order of the harmonics which have reduction factors equal to that of the fundamental remains constant. If the actual number of stator slots per pole per phase had been increased, then the order of this harmonic would have also increased.

An examination of Figs. 7, 8 and 9 shows that, when super-distribution of the windings is employed, the conductors of either phase are distributed in a number of slots per pole greater than the actual number of stator slots per pole per phase.

Let $\sigma =$ (slots occupied per pole per phase) − (actual stator slots per pole per phase).

Then, with unskewed slots,

$$\frac{\text{Reduction factor of } n\text{th harmonic super-distribution}}{\text{Reduction factor of } n\text{th harmonic normal distribution}} = \cos \tfrac{1}{2}\sigma n\psi$$

In those cases of two coil-sides per slot, where super-distribution is used, the reduction factors are given by

$$\frac{\sin \frac{1}{2}nm\psi}{m \sin \frac{1}{2}n\psi} \cos \tfrac{1}{2}\sigma n\psi$$

Thus super-distribution in stator windings with two coil-sides per slot may be of very great assistance where a sinusoidal distribution of the air-gap flux is desired.

Skewing the slots through one slot-pitch would also improve matters because, as has been shown, it prevents any harmonic having a reduction factor equal to that of the fundamental.

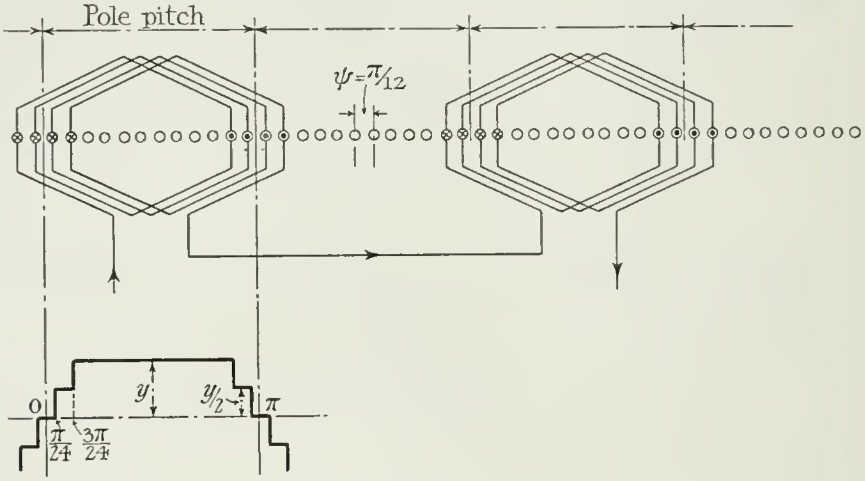


FIG. 10.—Four-pole half-coiled three-phase winding; normally distributed; 4 unskewed slots per pole per phase.

### IV. COIL DISTRIBUTION IN POLE-CHANGING INDUCTION MOTORS.

In these motors it is assumed at first that the stator windings are normally distributed when the motor operates with the greatest number of poles, and that super-distribution is brought about when the number of poles is decreased.

Fig. 10 shows one phase of a 4-pole, half-coiled, three-phase winding with four unskewed slots per pole per phase and it is immaterial, since the coils are normally distributed, whether there are one, or two, coil-sides per slot.

The reduction factors for this case, as shown on page 1088, are given by

$$\tfrac{1}{2}\left(\cos \frac{n\pi}{24} + \cos \frac{3n\pi}{24}\right)$$

Fig. 11 shows the same phase when the stator coils are grouped to form two poles. The winding is now whole-coiled and super-distributed, and the number of slots per pole per phase has increased to eight. That the winding is super-distributed can be seen from Fig. 11 which shows that the coils of one phase are grouped in slots 17, 18, 19, 20, 29, 30, 31 and 32, and that the coils of the other phases are introduced between them.

The reduction factors for the M.M.F. curve in this case are given by

$$\tfrac{1}{4}\left(\cos \frac{9n\pi}{48} + \cos \frac{11n\pi}{48} + \cos \frac{13n\pi}{48} + \cos \frac{15n\pi}{48}\right)$$

It is not proposed to obtain a relationship between the reduction factors for Fig. 10 and those for Fig. 11, owing to the fact that the number of slots per pole per phase is not alike in both cases.

The reduction factors for the M.M.F. curve of normally distributed coils with eight unskewed slots per pole per phase are given by (see page 1088)

$$\tfrac{1}{4}\left(\cos \frac{n\pi}{48} + \cos \frac{3n\pi}{48} + \cos \frac{5n\pi}{48} + \cos \frac{7n\pi}{48}\right)$$

It will be seen that the expression for the reduction factors in the super-distributed case is a portion of the same series as that which expresses the reduction factor for the normally distributed case, using the same number of unskewed slots per pole per phase. Evaluating the reduction factors for the normally distributed 4-pole case and the super-distributed 2-pole case, Table 5 is obtained.

TABLE 5.

| Order of harmonic | 4-pole, normal distribution; 4 slots per pole per phase | 2-pole, super-distribution; 8 slots per pole per phase |
|---|---|---|
| Fundamental | 0·958 | 0·70 |
| 5th | 0·205 | −0·534 |
| 7th | −0·158 | 0·385 |
| 11th | −0·126 | −0·069 |

From Table 5 it is seen that the most noticeable features of the change from four to two poles are :—

(*a*) The great decrease in the reduction factor of the fundamental, which means that the magnetizing ampere-turns are inefficient when the motor operates on two poles.

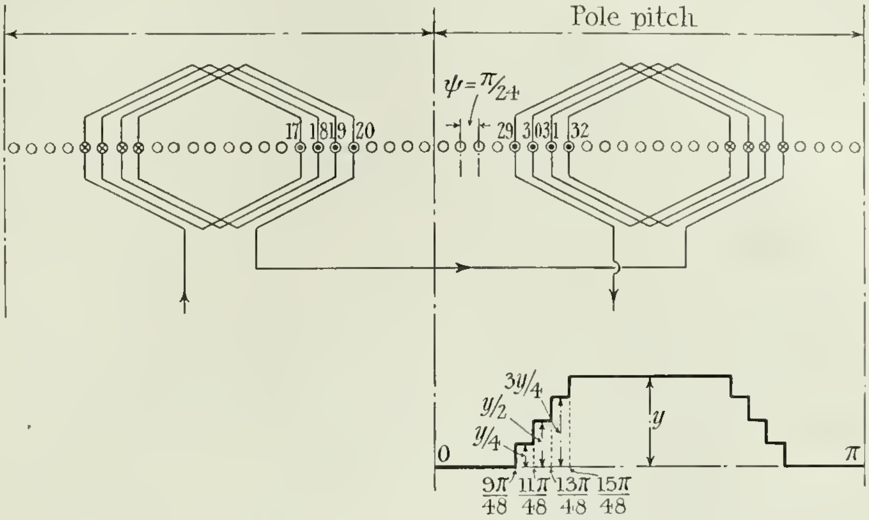

Pole pitch
$\psi=\pi/24$
17 18 19 20
29 30 31 32
$3y/4$
$y/2$
$y/4$
0
$y$
$\pi$
$\frac{9\pi}{48}$ $\frac{11\pi}{48}$ $\frac{13\pi}{48}$ $\frac{15\pi}{48}$

FIG. 11.—Two-pole whole-coiled three-phase winding; super-distributed; 8 unskewed slots per pole per phase.

(*b*) The large increase in the reduction factors of the fifth and seventh harmonics, which involves a serious risk of the motor crawling at a sub-synchronous speed if it is started up from rest on two poles.

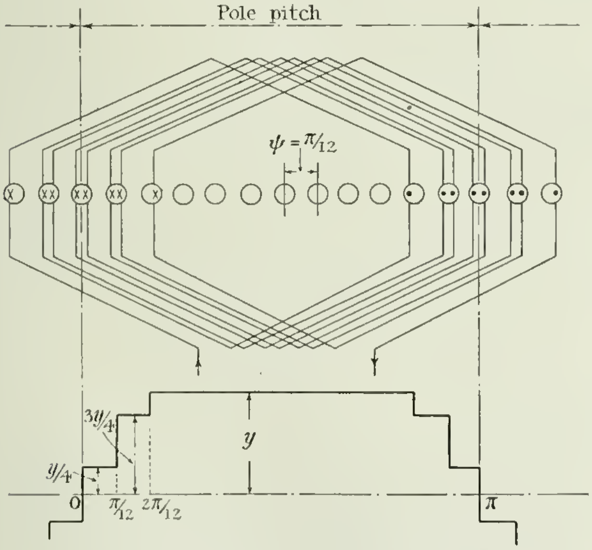


FIG. 12.—Four-pole half-coiled three-phase winding; super-distributed; 4 unskewed slots per pole per phase.

If the windings had been initially super-distributed on four poles with four unskewed slots per pole per phase, as in Fig. 12, then, as has been shown, the reduction factors would be given by

$$\tfrac{1}{2}\left(\cos\frac{n\pi}{24}+\cos\frac{3n\pi}{24}\right)\cos\tfrac{1}{2}\sigma n\psi$$

(NOTE.—In this case there are two coil-sides per slot and $\sigma = 1\cdot0$ since the number of slots occupied per pole per phase is five, and the actual number of stator slots per pole per phase is four.)

If, now, the windings are regrouped to form a 2-pole stator, Fig. 13, which shows one pole-pitch only, is obtained. In this case the winding also has super-distribution.

If Fig. 11 is termed the 2-pole case of "no initial super-distribution," i.e. when operating as a 4-pole machine the distribution is normal, then Fig. 13 can be described as the 2-pole case of "initial super-distribution," i.e. there is super-distribution when operating as a 4-pole machine.

The reduction factors for Fig. 11 (no initial super-distribution) have been shown to be equal to

$$\tfrac{1}{4}\left(\cos\frac{9n\pi}{48}+\cos\frac{11n\pi}{48}+\cos\frac{13n\pi}{48}+\cos\frac{15n\pi}{48}\right)$$

The reduction factors for Fig. 13 (initial super-distribution) are given by

$$\tfrac{1}{8}\left(\cos\frac{8n\pi}{48}+2\cos\frac{10n\pi}{48}+2\cos\frac{12n\pi}{48}\right.$$
$$\left.+2\cos\frac{14n\pi}{48}+\cos\frac{16n\pi}{48}\right)$$

In this 2-pole case also, it can be shown that the ratio

$$\frac{\text{Reduction factor } n\text{th harmonic initial super-distribution}}{\text{Reduction factor } n\text{th harmonic no initial super-distribn.}}$$

$= \cos\tfrac{1}{2}\sigma n\psi$, where $\sigma$ is the amount of the initial (4-pole) super-distribution. This ratio, therefore, is unaffected by the change in the number of poles except in so far as the value of $\psi$ changes. In the 4-pole case considered, $\psi = \pi/12$, whilst in the 2-pole case $\psi = \pi/24$.

In Table 6 the reduction factors have been evaluated for different values of $\sigma$, that is, for different amounts of initial super-distribution.

(NOTE.—When $\sigma = 0$ the initial distribution is normal.)

TABLE 6.

| Order of harmonic | 4 Poles | | | | 2 Poles | | | |
|---|---|---|---|---|---|---|---|---|
| | $\sigma = 0$ | $\sigma = 1$ | $\sigma = 2$ | $\sigma = 3$ | $\sigma = 0$ | $\sigma = 1$ | $\sigma = 2$ | $\sigma = 3$ |
| Fundamental | 0·958 | 0·95 | 0·926 | 0·885 | 0·7 | 0·698 | 0·694 | 0·686 |
| 5th | 0·205 | 0·163 | 0·053 | −0·078 | −0·534 | −0·505 | −0·424 | −0·297 |
| 7th | −0·158 | −0·096 | 0·041 | 0·146 | 0·385 | 0·346 | 0·234 | 0·075 |

From Table 6 it is seen that for the 4-pole case considered, with four slots per pole per phase and two coil-sides per slot, the best all-round results are obtained by making $\sigma = 3$, that is, by making the windings of either phase occupy seven slots per pole instead of four. A device to cut out the torque due to any harmonic has been put forward by Prof. Catterson-Smith. It consists of a squirrel-cage rotor the bars of which are spaced so that the distance between them is equal to two pole-pitches of the harmonic to be eliminated, and if necessary two separate cages can be fitted to the rotor. If with $\sigma = 3$ in the above example the rotor bars were spaced to suit the 2-pole, fifth harmonic, the motor would have no tendency to crawl on either four or two poles.

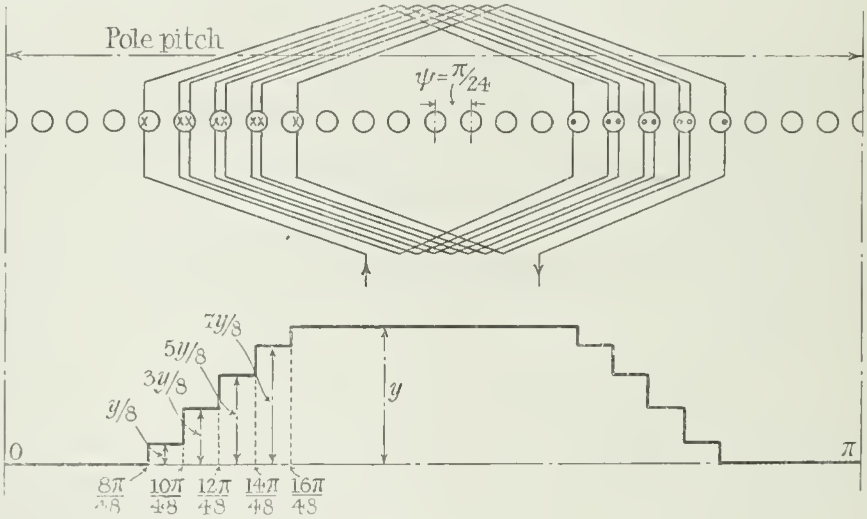


FIG. 13.—Two-pole whole-coiled three-phase winding; super-distributed; 8 unskewed slots per pole per phase.

### V. THE ESTIMATION OF THE CHANGE IN THE MAGNETIZING CURRENT WHEN THE NUMBER OF POLES IS CHANGED.

In considering the changes which take place in the magnetizing current of a motor when the number of poles is changed, it must be remembered that the back E.M.F. per phase is a function of the manner in which the conductors of that phase are distributed in space. This is due to the fact that the E.M.F.'s in the various coil-sides do not reach their maximum values at the same instant, but have phase differences proportional to the angles (electrical degrees) between the coil-sides.

This fact is taken into account by introducing a "breadth factor" into the equation for the phase E.M.F.

It is easily proved that these breadth factors are numerically equal to the reduction factors, $X$, of the harmonics in the M.M.F. curves, and that the R.M.S. value of the fundamental back E.M.F. (a sine curve) in a normally distributed three-phase motor with an average number of slots per pole per phase is

$$E = 0 \cdot 96 \left( \frac{4 \cdot 44}{\pi} B_{max.} AZf\,10^{-8} \right)$$

where $A$ = pole area,
$Z$ = number of conductors per phase in series,
and $f$ = frequency.

In order to test the accuracy of the foregoing notes, some experiments were made on a pole-changing motor installed in the Laboratories of Applied Electricity, Liverpool University. The winding diagrams for this motor are set out in Figs. 10 and 11, the fundamental reduction and breadth factors being as shown in Table 5.

In changing from four to two poles,

$E$ is constant, since the applied stator voltage is constant;
$Z$ is constant, as is seen from Figs. 10 and 11;
$A$ (the pole area) is doubled.

So that the ratio of the maximum flux densities in the air-gap is obtained from

$$0\cdot958\, B_4 A_4 = 0\cdot7\, B_2 A_2$$

i.e.
$$\frac{B_4}{B_2} = \frac{2 \times 0\cdot7}{0\cdot958} = 1\cdot46$$

This shows that a reduction in the number of poles causes a reduction in the value of the maximum flux density in the air-gap. An experiment to test this consisted in separating the no-load iron loss from that due to windage and friction for both 4-pole and 2-pole operation.

The ratio of the iron losses was found to be

$$\frac{W_4}{W_2} = 1\cdot6$$

which is perhaps a little low for the estimated ratio of $B_{max.}$ To allow for this change of flux when estimating the magnetizing current taken by the motor, the following method is adopted.

The harmonics in the M.M.F. curve are neglected, and in any case their R.M.S. value is small except when operating on two poles.

Let $p$ = the number of poles.
$I$ = the R.M.S. value of the magnetizing current per phase.

Then $\sqrt{2}IZ/2p$ = the maximum value of the ampere-turns per pole in the M.M.F. curve of one phase when the windings are massed in one slot per pole per phase.

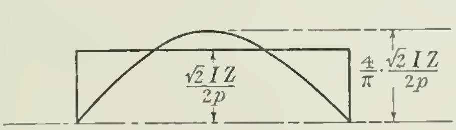

$\frac{\sqrt{2}\, I Z}{2p}$
$\frac{4}{\pi} \cdot \frac{\sqrt{2}\, I Z}{2p}$

FIG. 14.

As has been shown, the maximum height of the fundamental in this case is given by (see Fig. 14)

$$\frac{4}{\pi} \times \frac{\sqrt{2}IZ}{2p}$$

If the windings are arranged in any other manner, then the maximum height of the fundamental is given by

$$\frac{2\sqrt{2}}{\pi} \times \frac{ZI}{p} \times \text{Reduction factor}$$

For all three phases taken together the maximum height of the fundamental is given by

$$1\cdot5 \left(\frac{2\sqrt{2}}{\pi} \cdot \frac{ZI}{p} \times \text{Reduction factor}\right)$$
$$= 1\cdot35 \frac{ZI}{p} \times \text{Reduction factor}$$

The R.M.S. magnetizing current per phase for an air-gap of length $l$ and maximum flux density equal to $B_{max.}$ is obtained from

$$1\cdot35 \times \frac{ZI}{p} \times \text{Reduction factor} = 0\cdot8\, B_{max.}\, l$$

from which $I = 0\cdot59 \times \dfrac{B_{max.}\, l \cdot p}{Z \times \text{Reduction factor}}$

A certain percentage, depending on the saturation of the iron, is added to this to allow for the ampere-turns required for the iron part of the magnetic circuit.

If 20 per cent is added in the 4-pole case, then

$$I_4 \propto \left(\frac{0\cdot59 \times 4}{0\cdot958}\right) + 20 \text{ per cent}$$
$$\propto 2\cdot96$$

Allowing for the reduction in the value of the maximum flux density in the 2-pole case, by adding 5 per cent,

$$I_2 \propto \left(\frac{0\cdot59 \times 0\cdot684 \times 2}{0\cdot7}\right) + 5 \text{ per cent}$$
$$\propto 1\cdot21$$

The estimated ratio of the magnetizing currents is

$$\frac{I_4}{I_2} = \frac{2\cdot96}{1\cdot21} = 2\cdot45$$

The actual value of the ratio, determined by experiment, was

$$\frac{I_4}{I_2} = \frac{7\cdot55}{2\cdot8} = 2\cdot6$$

## VI. THE EFFECT OF SATURATION.

If all the iron in the neighbourhood of the air-gap is saturated, then the flux distribution in the air-gap will not follow the pronounced step characteristic of the M.M.F. curve. The corners will be rounded off and the magnitude of the harmonics will be greatly reduced.

Thus, when the particular motor on which these experiments were made operates on four poles, it shows no tendency to crawl on starting up, even when the supply voltage is lowered to half the normal value.

When it operates on two poles the reduction in the value of the flux density causes the step characteristic to become pronounced and the harmonics very prominent. This is confirmed by the fact that the motor fails to accelerate above the seventh harmonic synchronous speed when started up from rest on the normal voltage.

It should also be remembered that the use of partly closed stator and rotor slots would tend to eliminate the steps in the M.M.F. curve from the curve of flux distribution, if the slots were not set too near the bore.

If the slots are very near the bore, then the horns of the teeth will be highly saturated when the flux density in the main parts of the teeth is quite low, and the consequent flux distribution will not differ from that obtaining with open slots. In the case of the motor referred to here, the stator slots are 25 per cent open and the rotor slots are 16 per cent open, but both sets of slots are placed very near to the bore.

This reduction in the flux density when the number of poles is reduced makes it very necessary to employ a suitable design of winding, since it is not feasible to operate on the largest number of poles at such a high flux density that, when the number of poles is reduced, the density is still high enough to smooth out the harmonics.

In conclusion, the author wishes to thank Prof. E. W. Marchant, D.Sc., for permission to publish the details concerning the 4/2-pole induction motor which forms part of the laboratory equipment in the University of Liverpool, and to Mr. T. W. Dann for his assistance in making the necessary tests.

---

# WIND-DRIVEN GENERATORS.

By W. Stirling, Student.

(Abstract *of paper read before the* Scottish Students' Section, 12*th January*, 1923.)

## Summary.

The paper describes the various sources of power for the generation of electricity in small quantities. Former objections to wind-power sets are stated, and the paper proceeds to show how these have been overcome. Wind-driven generating sets in general are described, particular attention being given to a novel form. The actual results of a plant are given for the period from July to December.

## Introduction.

Water and wind are the two most obvious sources of power, and both have been utilized from early times. The inherent advantages of steam power about a century ago seriously curtailed wind power development, but lately the increase in the cost of fuel has compelled renewed investigation.

The advantage of water power is that, where ample volume and head are available, considerable power can be converted at one point. This at times is a distinct disadvantage, as in some cases the most suitable sites for a station are in most inaccessible positions, for example, in glens and mountains. To convey the power to a suitable market the electricity is transmitted at a high voltage to the nearest centre. It is obvious, therefore, that a hamlet or farm will not consume enough power to warrant the installation of a transformer. There is thus the anomaly of persons desirous of using electric power being unable to do so although the supply cables are close at hand. A wind-power set is, however, very suitable for this class of consumer. The more exposed the situation, the more power will be available; and the more isolated it is, the more evident is the advantage of being independent of the transport of fuel. Further, any reasonable demand can be met by making the size of the wheel large enough, and the most wind is available when most light is required, that is, in winter.

## Former Objections.

The chief objections against wind-driven lighting sets until now have been: (1) the large wheel necessary to generate sufficient power, and (2) the large battery required as a stand-by in calm weather. Both these objections have been partly overcome by the improvement in the construction of the electric lamp, the gas-filled type requiring only from one-quarter to one-eighth of the power of the earlier carbon-filament type. Improvement in design overcomes the remainder of the first objection, while the second objection is not so formidable as it might appear. Calm days are much rarer than is popularly supposed, when the day of 24 hours is taken into consideration.

## Extraction of the Power.

(A) *Wind wheel.*—Since the power in the wind is due, almost entirely, to velocity head it is obvious that the wind wheel must be of the turbine type. For maximum efficiency, (1) the relative velocity at inlet should equal the absolute velocity of the blade, and (2) the whole blade should move with uniform velocity. In the type of wind wheel in which the velocity of approach is along the axis of rotation of the wheel, neither of these conditions can be fulfilled. A more highly efficient engine could be obtained by guiding the wind by stationary vanes as in the turbine, but the extra power can be more easily obtained by making the wheel a little larger. Also there is a limit to the useful length of the blade, and in practice this has been found to be one-third of the diameter of the wheel. The best angle at the inlet has also been found to be 30°. With long blades, the discrepancy between the correct velocity of the blades and the actual velocity of their extremities will increase as the velocity of the wind increases, which means that the efficiency will decrease as the velocity of the wind increases. Although this is unfortunate from one point of view, it is an advantage that the efficiency should be a maximum at low wind velocities, as it is the light-breeze efficiency which determines the efficacy of the plant since the prevailing winds are at low velocities.

Another point in the design of the wheel is that the relative velocity of the wind is half its actual velocity, which means that the pressure on the wheel is only one-quarter of what it would be if the wheel were stationary. This, however, is only true if the wind is steady. If the weather is gusty, the wheel will not always be moving at its correct speed and the pressure will be greater than the theoretical. Some modification of the design to allow for this is therefore necessary.

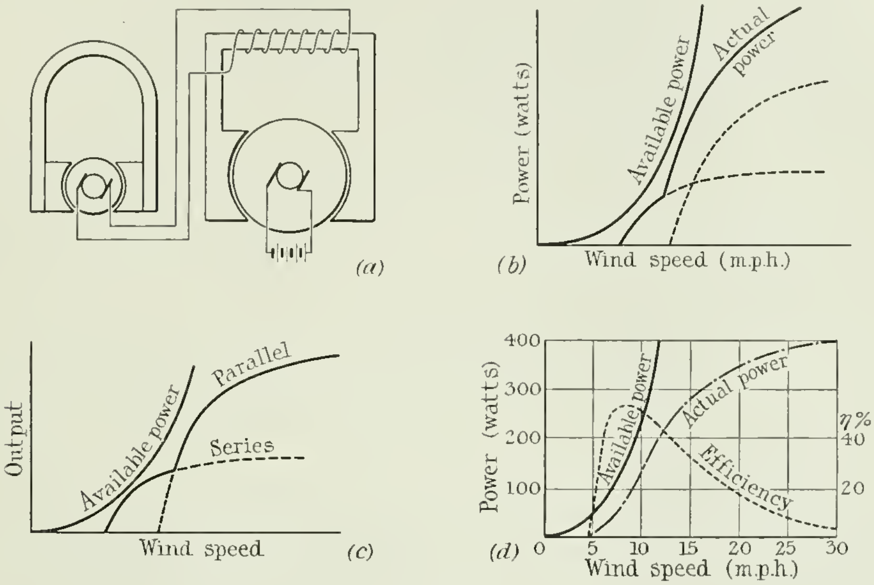


Fig. 1.

(B) *Generator.*—The wind-driven dynamo is, of necessity, a variable-speed machine, and means must therefore be provided to enable it to run automatically at its theoretically correct speed at all wind velocities. The available energy in the wind can be expressed in the form $\frac{1}{2}mv^2$, and, as the mass impinging per second is itself proportional to the velocity, the energy must vary as the third power of the velocity. That is, if the wind velocity is doubled, the available power is not twice but 8 times as great. Now when the wind speed is doubled, the wheel speed is also doubled, and therefore the torque should be 4 times as great.

An interesting type of generator is shown in Fig. 1(*a*). A permanent-field exciter excites a shunt-wound generator to which it is direct coupled. The field strength of the second machine varies as the speed, and, since the armature voltage also varies as the speed, the output of the main generator varies as the square of the speed. This arrangement would, however, be extremely clumsy as the magnetization of the generator would always have to be well below the knee of the saturation curve in order to preserve the straight-line characteristic, which would mean a very large machine. A simple compromise is to have a cumulative compound-wound generator, which would automatically increase the field strength as the output increased. Although this form of generator is generally prohibited in battery-charging sets, because of possible reversal of excitation when the speed drops, with a modern automatic reverse-current circuit-breaker this objection is removed.

Another method which has enjoyed some popularity in the past is to have a low-speed shunt-wound generator of small power in parallel with a shunt-wound generator of higher speed and power, both generators being fitted with independent reverse-current switches. The smaller machine comes into action with light winds and is soon working at full load and maximum efficiency. When armature reaction tends to limit the output, the second machine is switched in and the sum of the currents gives an approximation to the required characteristic, as shown in Fig. 1(*b*). The main disadvantage of the arrangement is that there are the losses of two drives and two machines, which will hamper the efficiency at the lower wind speeds. Another method is one in which two windings are laid in one armature core, each fitted with a commutator. At low speeds the two windings are in series, but at the predetermined time a centrifugal switch changes them over to parallel connection. The advantage is that there are the losses of one machine only, and also that it is working at full load both at low and high speeds, as indicated in Fig. 1(*c*). For sets of smaller power up to 500 watts, it is found that sufficient approximation is obtained with a pure shunt-wound machine specially designed to have very low armature reaction so that the resulting saturation curve is approximately a straight line. Since, after all, the limiting condition is the heating of the copper of the armature windings, a very highly corrected generator is not necessary. Fig. 1(*d*) shows the curves actually obtained with a 400-watt set, the efficiency of the whole set rising to 53 per cent at 7 miles per hour, and then gradually falling away as full power is reached and the power curve flattens out.

A point which will be obvious when attention is drawn to it, but which may otherwise escape notice, is that the generator efficiency is a maximum at a lower output when the battery is almost discharged than when it is completely charged. This is due to the fact that at lower voltages the iron and windage losses are less for a given current than they would be in the higher regions. This effect is much more noticeable than it would appear at first glance and may displace the peak of the efficiency curve of the dynamo from 300 watts to 200 watts. This is, of course, most fortunate as it is when the battery is exhausted after a prolonged calm that it should be most susceptible to light breezes. Again, it will be seen that when the generator is housed at the wind wheel it will be best ventilated by the wind when it is working at maximum output, i.e. during a storm.

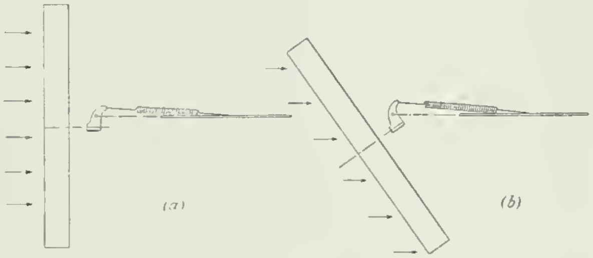


FIG. 2.

In every respect, therefore, the wind dynamo is in a most favourable position as its efficiency is highest when most required and is best fitted for heavy duty when that duty is demanded of it.

*Governing.*—All windmills are fitted with some governing device to limit the output when the wind velocity exceeds a predetermined maximum. This has usually been done by erecting the wind wheel eccentrically so that it tends to be blown out of the wind. It is kept in the wind by means of a tail to which it is connected through a spring. When the wind is too strong the eccentric pull overcomes the spring, which then extends and causes the wheel to go out of the wind. Fig. 2(*a*) shows the wheel and tail in a light wind, and Fig. 2(*b*) in a strong wind, with the governor allowing the wheel to go partly out of the wind.

*Design of tower.*—When the power is transmitted mechanically, the shaft or rod, as the case may be, must pass down the geometrical centre of the structure to ensure the gears being in mesh while the wind wheel turns bodily about the vertical axis in order to follow the wind. This implies that the structure must be rigid, hollow, and of sufficient diameter to allow the shaft plenty of room. In short, the wheel must be erected on a lattice tower. When, however, the power is converted into electricity at the wheel and transmitted to the ground through slip-rings, such a structure is no longer necessary and is not desirable if any other is suitable. The disadvantages of the lattice tower are:—

(1) There are many parts, all of different sizes, which must be bolted or riveted together on the site, necessitating time both in assembling and erecting.

(2) Concrete foundations are necessary owing to the small span of the base.

(3) The assembling is commenced at the ground and the tower has to be built *in situ*. The wheel and its fittings have to be carried up the tower piecemeal, and fitted in position and tested up in the air.

(5) The material of which the tower is made is subjected alternately to compression and tension according to the direction of the wind. This means that fatigue from reversal of stress may ensue, and ultimate failure may take place.

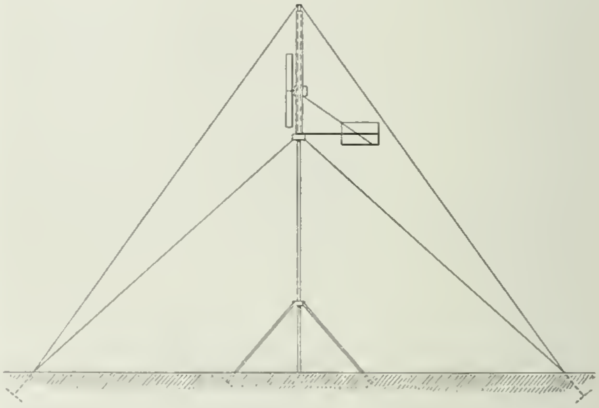


FIG. 3.

The structure shown in Fig. 3 has the following advantages over the lattice tower:—

(1) It is much lighter.

(2) It consists of fewer parts.

(3) The mast can be assembled on the ground and pulled into place as one member.

(4) The wheel, tail, governor, drive, etc., can be assembled and tested on the ground level and finally pulled up into position and fixed by the addition of four bolts.

(5) No concrete foundations are necessary.

The general principle of the structure is that the "head" consists of a simply supported beam which takes all the bending and transmits the horizontal wind pressure to the pole at the apexes of the two sets of guy ropes. The pole is thus put in a state of compression, the guy ropes in tension, and the "head" is subjected to bending in one direction only (as it follows the wind together with the wheel and tail), no matter from which direction the wind may be blowing. There is thus no reversal of stress and, the span being great, the loading is very light. The head is in the form of a steel channel so that the mast with its two sets of guy ropes may be completely fitted and the head then hoisted and pushed home into position sideways.

### Results.

The performance curve of a set installed on the coast of south-west Scotland is shown in Fig. 4. The set is rated at 400 watts maximum output at 25 volts, the diameter of the wind wheel being 8 ft. The set supplied a boarding house with current for 40 15-watt lamps, which accounts for the heavy demand made during July and August. The full line indicates the reading of an ampere-hour meter set 20 per cent slow on the charge side and reading correctly on discharge in order to compensate for the battery efficiency. The dotted line indicates the consumption each night. On two occasions, viz. 11th August and 25th November, the demand has apparently exceeded the storage, but this is due to the fact that the current consumed was being generated by the dynamo at the time without going through the cells or meter, and, had the lamps not been burning, the meter reading would have shown a sudden rise. This property of the "floating battery" is one of the great advantages of the wind set, as not only is its efficiency much higher but its life is longer than under the more trying conditions of sudden charge and discharge inherent in petrol-driven sets. During the 6 months of the charge it will be noticed that the longest period of complete calm was from 19th October to 30th October. The late autumn is always the most unsatisfactory time of the year, due to the lengthening nights and sultry weather, but if the battery is of sufficient size to keep the house lighted for about a week, this period should be successfully passed. On several occasions, viz. 30th August, 16th and 20th September, 13th October, 2nd, 8th and 12th November, and 6th, 12th, 13th, 14th, 15th and 16th December, the mill was pulled out of the wind, as the cells were gassing.

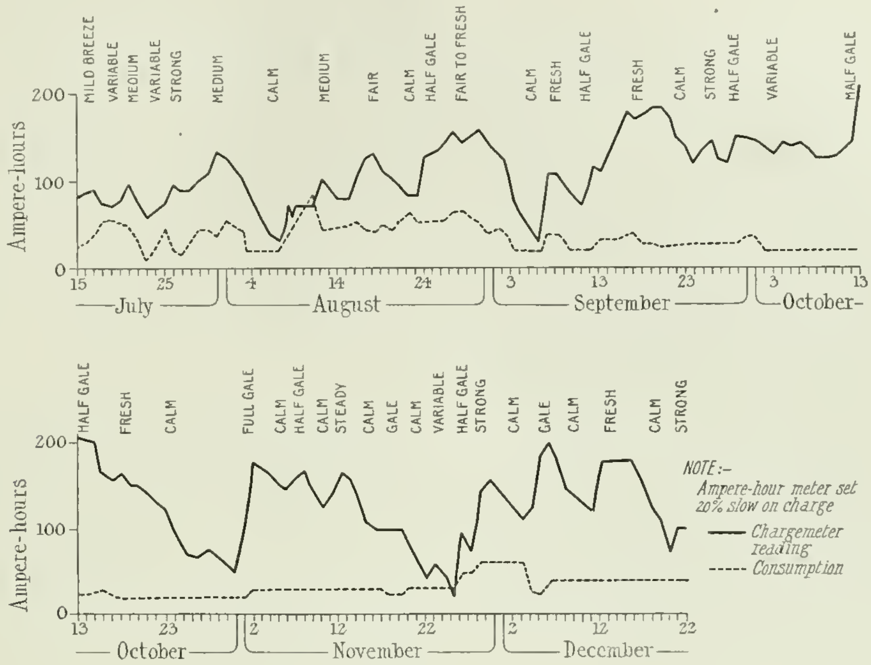


Fig. 4.

# THE ELECTRIC BATTERY VEHICLE.

By H. E. Dance, Student.

(Abstract *of paper read before the* Liverpool Students' Section, 14*th November,* 1922.)

## Summary.

In the original the paper was intended to review the whole of the position of the electric battery vehicle as it stands to-day. In the present abstract the descriptive sections dealing with the battery, chassis and charging equipment have been omitted, attention being confined to the more important sections.

The paper opens with a reference to the early failure of the electric battery vehicle and to the misconceptions which exist as to its proper duty.

The battery is not dealt with in detail, but a table showing the characteristics of the two chief types is included, while the motor is dealt with by a brief reference to the main factors controlling its design.

The question of transmission is discussed at length, as is also the subject of control. Under the heading of transmission the special circumstances affecting differential action are noted.

As information regarding the methods of charging is not readily accessible, it was decided to devote a section to this subject which is probably of greater interest to the user than that of the battery itself.

Space does not permit of any considerations of the financial aspect of the question. For information on this point reference should be made to the papers by Mitchell and Watson [*] and L. Brookman,[†] in which the matter is discussed at length.

## Introduction.

The history of the electric battery vehicle is one of a premature development which endowed it with a series of misconceptions and false impressions that hamper it even to-day.

There are so many factors necessary to the success of the electric vehicle, e.g. first-class batteries, suitable charging stations, proper education of the public, etc., that the attempts to develop it at such an early date could be nothing but failures.

During the past 20 years all the factors have been steadily improved, and to-day the electric vehicle stands in a class of its own—a transport machine of the highest rank and reliability.

Before discussing any of the details of the battery vehicle let us consider what its real duty is. Reviewing the transport situation in our great cities we find high-speed and long-distance goods traffic being handled by gas trucks, while a large percentage of local haulage is done by the horse.[‡]

The electric battery vehicle can compete with, and economically replace, the horse wagon; but the gas truck cannot do so. Thus the electric vehicle is not intended to replace existing mechanical methods, but to take its place in the great change-over to entirely mechanical transport.

It is a misconception of its proper application which leads to an off-hand condemnation of the battery vehicle on account of its comparatively low speed. It travels slowly because it is designed to do so. When working in congested areas the majority of the time is wasted in accelerating and retarding, and it is impossible to move much faster than the mean traffic speed, which is well below the normal range of the electromobile.

For these reasons we are not likely to see any deviation from the present speed rating in battery traction for some time.

## The Storage Battery.

Although the storage cell is the one factor which limits the scope of the electric vehicle to-day, it is not intended to discuss it at length here. The subject of batteries has already been dealt with in a very thorough manner by several authors, and in any case it is large enough to demand a paper for itself.

It will suffice to give here a comparative statement of the characteristics of the lead and the nickel-iron cells and to mention that in Great Britain the former is in more common use. The particulars of the two types are :—

| | Lead cell | Nickel-iron cell |
|---|---|---|
| Efficiency .. | 75 per cent | 65 per cent |
| Internal resistance | Low | High |
| Effect of low temperature | Practically nil | Decrease in capacity |
| First cost .. | Low | High |
| Life .. .. | 2 years | 6 to 8 years |
| Container .. | Hard rubber (breakable) | Metal (must be insulated) |
| Electrolyte .. | Acid | Alkaline solution |
| Capacity (watts per pound) | 10·33 | 15 |
| Equalizing charges | Every 14 days | Not essential |
| Fall in capacity on high-discharge rates | High | Low |
| Self-discharge .. | Small | High immediately after charge, then low |
| Possibilities of boost-charging | Limited by gassing and temperature | Limited by temperature only |

---

[*] W. H. L. Watson and R. J. Mitchell: "Electric Automobiles," *Proceedings of the Incorporated Municipal Electrical Association*, 1913, p. 58.

[†] L. Brookman: "Self-propelled Electric Vehicles," *Proceedings of the Institution of Engineers and Shipbuilders in Scotland*, 1917, vol. 40, p. 94.

[‡] About 75 per cent of local city traffic is horse-drawn.

### The Motor.

The type of transmission does not interfere to any great extent with the electrical design of the power unit, although the mechanical details may require adjustment to meet individual demands.

In designing the motor a compromise must be made between the conflicting claims of light weight and high efficiency. The price and weight of the battery are items so large compared with those of the motor that it is sometimes more economical to use a rather heavier, more costly, but more efficient machine than to install the larger battery which a cheap, low-efficiency motor would demand in order that mileage may be maintained.

Fig. 1 shows typical characteristics of a good class of series machine. The curves are based on an assumed drop in terminal voltage of 25 per cent when the machine is taking an overload in current of 200 per cent; they apply to the motor arranged for normal working, i.e. with the fields in series-parallel. The lower curves apply to the same machine arranged with fields in series.

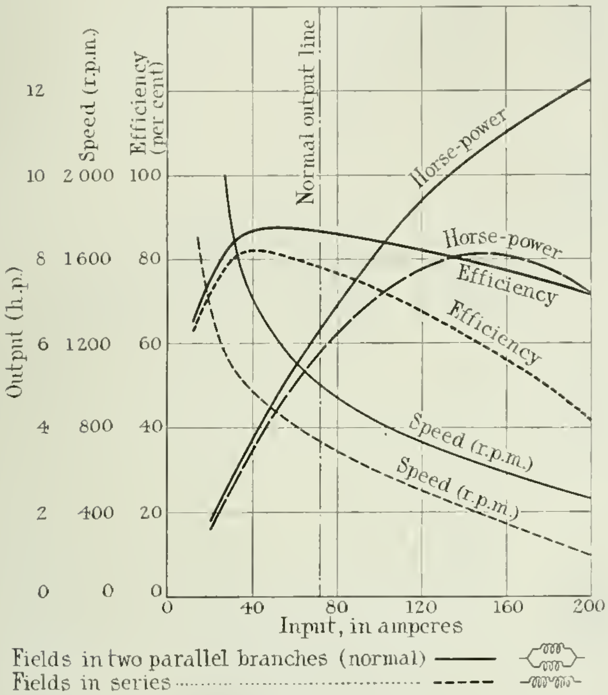


Fig. 1.

### The Transmission.

The design of the transmission of the gas truck has been limited to single-motor arrangements on account of the necessity of introducing a speed-changing gear between the engine and the live axles.

In the electric vehicle, when a high speed is desired, it may become necessary to fit a gear box to avoid excessive current and acceleration; but, in general, the limitations imposed on the arrangements of the transmission from the internal-combustion engine do not hamper the designer of the electric vehicle.

In spite of this the single-motor drive is of frequent application.

In this transmission the motor may have full benefit of the chassis springing without any derogatory effect on the efficiency of the gears.

Further, one large motor results in greater output per pound than a number of small machines of equal aggregate horse-power, and it will also be more efficient and capable of sustaining longer overloads.

Four of the more important single-motor transmissions are shown in Fig. 2 (*a*), (*c*), (*d*) and (*g*).

Fig. 2 (*j*) shows diagrammatically a single-motor drive* in which the transmission is through gears in the wheel itself. An advantage of this arrangement is that the motor, differential, transmission and reduction gears may be removed as a complete unit, but unfortunately the unsprung weight is high.

Fig. 2 (*b*), (*e*), (*f*), (*g*) and (*h*) shows various 2-motor drives of which (*g*) and (*h*) are worthy of notice, since the motor is in one unit with the wheel and removable with it. For this reason they are frequently applied to 4-wheel drives, interference between the power-transmission system and the steering action being thus eliminated.

The general tendency to-day is to adopt a single- or double-motor drive for light- and medium-weight vehicles and a double- or quadruple-motor drive for heavy vehicles. It is to be noted that the multiple-motor drives eliminate the differential gear.

Where the drive is of such a kind as to entail considerable unsprung weight it is necessary to fit specially resilient tyres. These result in an appreciable decrease in mileage on account of the increased internal tyre loss.

### Differential Action.

To keep tyre loss and wear to a minimum the differential action must be as perfect as possible.

The mechanical distribution of power from a single motor has already been perfected and does not call for comment here.

It has been stated that the use of two motors results in an automatic differential action. When two motors are used, however, they may be connected either in series or in parallel. When they are in series the currents, and consequently the torques, are equal and the sum of their speeds is approximately constant for equal conditions. These characteristics correspond to those of the ideal differential gear.

But if the motors are in parallel, the motor of the inner wheel will tend to take more load as the turning radius decreases, and in the extreme case, i.e. when the vehicle is turning about the vertical axis which passes through the centre of one wheel, the motor driving that wheel will be stationary and the battery will be short-circuited through it.

When turning on a large radius, however, the difference in speed and torque may be neglected.

From these considerations it will be seen that if a multiple-motor equipment is fitted, the control must be of the series-parallel type, so that at the low speeds at which sharp turns can be taken the machines will be in series.

---

* The Walker balance drive.

### CONTROL.

Of the different methods of obtaining various speeds, that in which the battery is connected in series-parallel combinations as shown in Fig. 3 (*b*) has much to be said for it on the score of simplicity, efficiency, high range and large starting capacity. In application, however, it is found that the large number of heavy cables which have to be brought to the controller are very cumbersome, and that the storage cell is not the most ideal source of power for parallel operation. The controller cannot be of the bridging type, and, unless it is in good hands, the speed regulation is uneven. This is very noticeable on the last step, when the voltage is doubled. Under certain circumstances it is possible to utilize an intermediate tapping [position X, Fig. 3 (*b*)] to reduce this jump, but on account of unequal discharging and consequent local currents such an arrangement is undesirable.

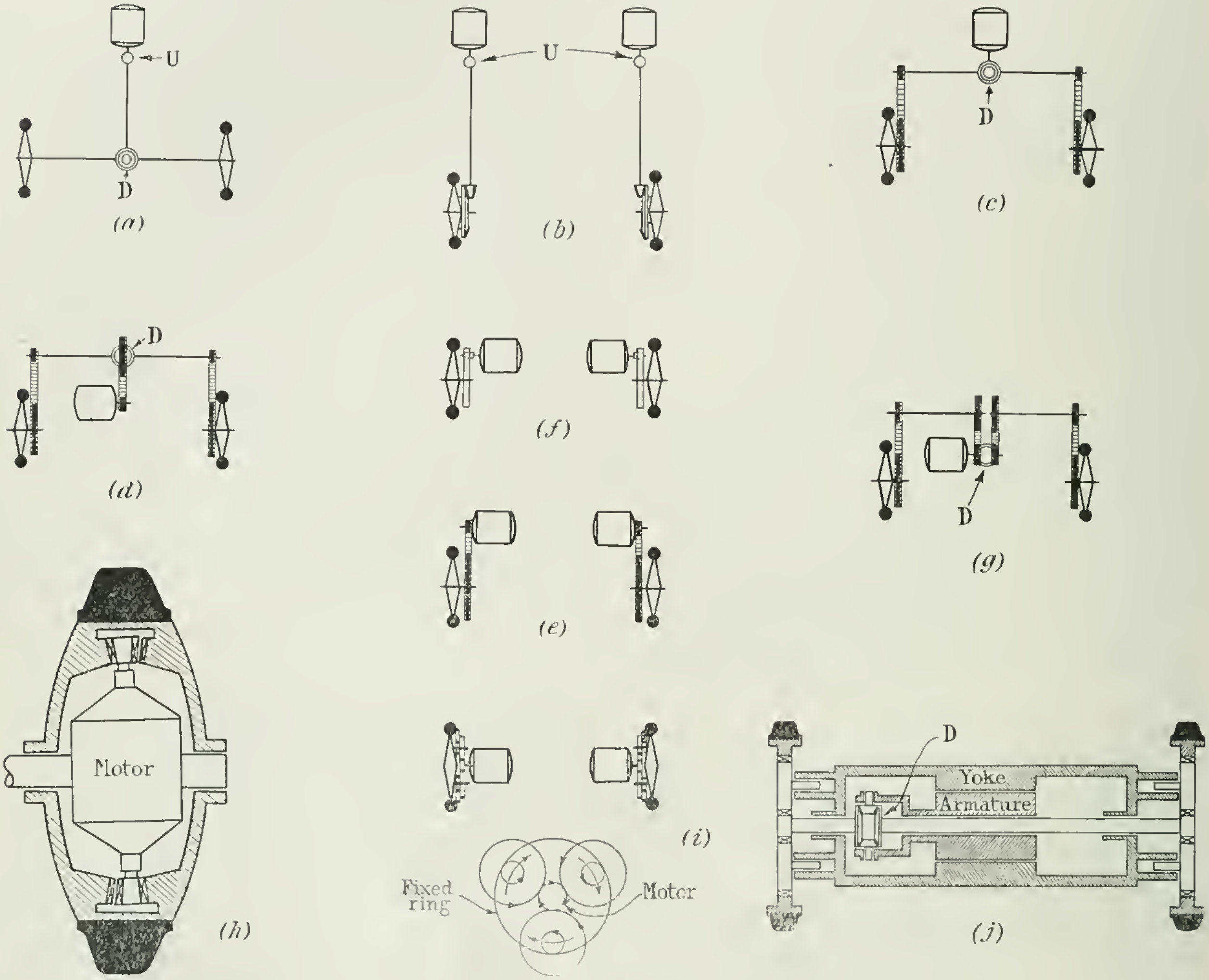


FIG. 2.

D = Differential gear. U = Universal joint.

It has been suggested that the battery control be applied with the two-parallel-branch position as the normal, the "all-in-series" position being retained for charging from 220-volt mains. As this voltage of supply is usually obtained from a three-wire system it is doubtful whether the supply company would welcome such a large out-of-balance load.

When an ampere-hour meter is used with the battery control it must be connected so as to read the current in one branch of the battery only, otherwise a fictitious capacity will be recorded.

The series resistance is rarely used alone for speed control on account of its inefficiency, its more usual application being in combination with some other form of control.

When a small series resistance is utilized for the first step it may be arranged so that after the normal speed has been reached it shunts a portion of the field current, as shown in Fig. 3 (*a*), so obtaining one or more speeds above normal.

In the series-parallel field control, Fig. 3 (*c*), the flux

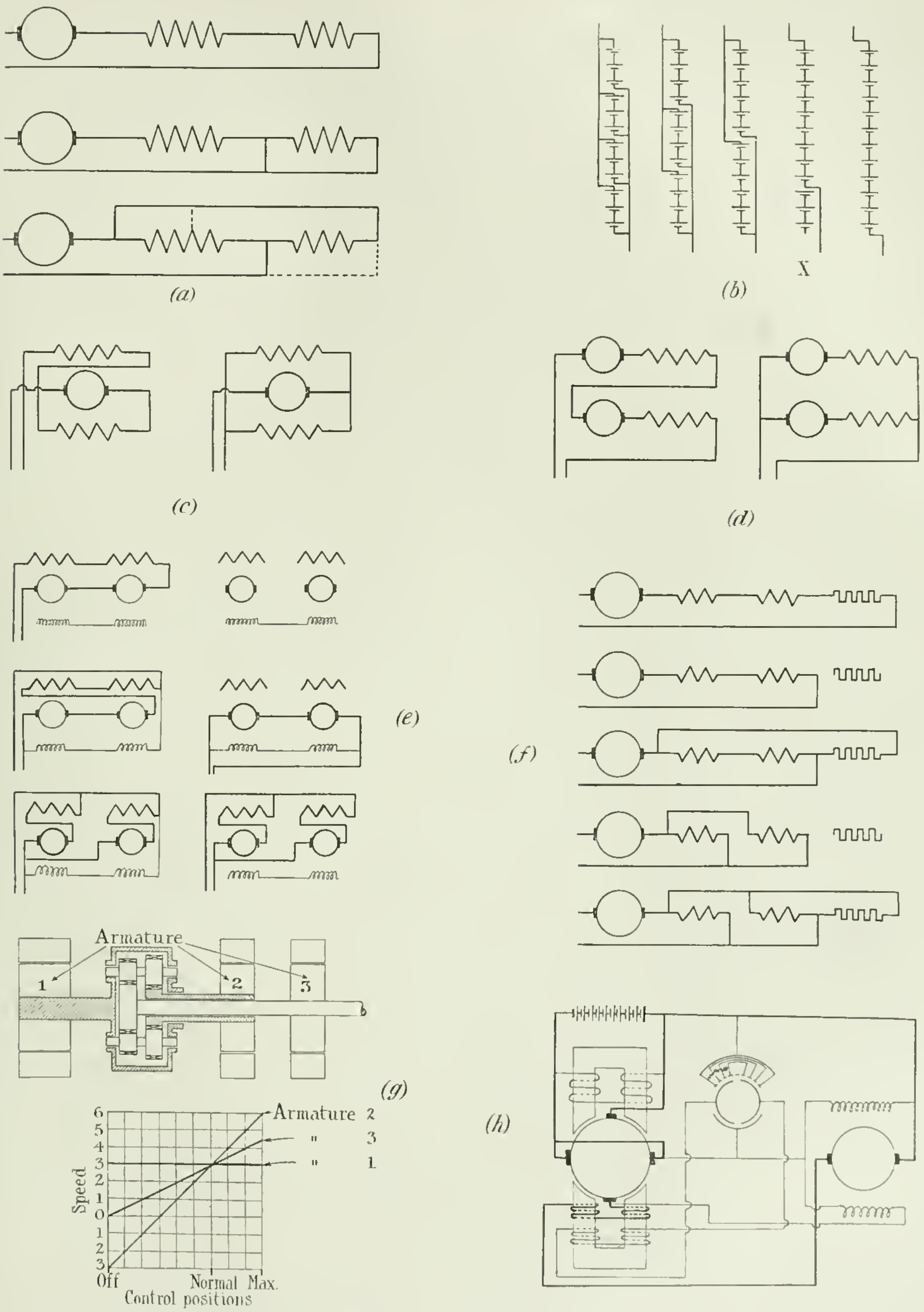


FIG. 3.—Showing various methods of control.

is varied by the re-arrangement of the exciting coils. The control may be used to obtain high torque at starting or for increasing the speed when running, but the regulation is somewhat coarse, the field strength being halved at each step. It is true that by subdividing the coils a finer regulation can be obtained, but this necessitates a more complicated controller, and, while this control is more efficient than the shunt or partial short-circuiting method (see Appendix 1), a careful combination of the two is often desirable, even at a small sacrifice of efficiency.

The series-parallel motor control, Fig. 3 (*d*), is well known to most students, and does not require description here.

When the motors are fitted with two independent armature windings on one core, it is possible to apply the series-parallel system to the armature windings themselves or to combine it with a similar system applied to the fields. It will be observed that such a combination enables the provision of two starting steps giving speeds of about one-half and one-quarter of normal speed and correspondingly increased torques (see Appendix 2).

By increasing the field at starting, the ratio of field ampere-turns to armature ampere-turns is increased. This is very desirable when dealing with heavy loads, but the increase in ampere-turns tends to saturate the iron, with the result that the torque does not increase nor the speed decrease in proportion. On the other hand, by leaving the field constant and connecting the two armatures in series at starting, saturation is avoided, but the ratio of field ampere-turns to armature ampere-turns is also decreased.

The use of motors with two armature windings has the advantage that by providing auxiliary shunt coils they may be worked as self-contained partial converters for charging purposes.*

Recent developments have been made in the use of regenerative control, the motors being fitted with special shunt windings, as indicated in Fig. 3 (*e*).

Most controls embody two or more of the methods enumerated above; there are, however, two systems which are definite departures from normal practice and which merit our closer attention.

*Crompton control.*†—This control consists of a very heavily differentially-compounded reversible booster in series with the battery. Driving the booster is a shunt motor excited from the battery. As the field coils of the booster are excited through a reversing switch [see Fig. 3 (*h*)], the following conditions are possible :—

(1) *Booster fields separately excited.*—The booster becomes a separately-excited generator, raising the battery voltage and being driven by the shunt-wound motor.

(2) *Booster fields not separately excited.*—The booster becomes a series motor, driving what was in Case 1 the shunt-wound motor, which latter now becomes a generator and supplies the complement of the current.

(3) *Booster fields separately excited but in the reverse direction.*—This is similar to Case 2, except that the booster now acts as a cumulatively-compounded instead of series-wound motor as previously.

In addition to the above arrangement the traction motor itself is modified, having two windings on the field, one excited from the battery and the other excited from the booster and arranged so that when the conditions of Case 1 hold, the two fields act differentially, that excited from the battery being in preponderance.

The result is a shunt motor in combination with the booster, arranged so that it has series characteristics. The combination also gives (1) a voltage decreasing with the load, (2) the motor field increasing with the load, and (3) a practically constant battery current.

The method lends itself to regenerative braking, while the controller is very light, having to handle small currents only. Another desirable feature is that the booster set may be used as a partial converter for charging purposes.

To reduce weight it is usual to embody the motor and generator in one machine. In Fig. 3 (*h*) the motor and generator windings are shown on the same core working in a field partly common to both.

*Thomas transmission.**—This was developed primarily to replace the change gear of the gas truck. It consists of three machines, mechanically coupled, their relative positions being as indicated diagrammatically in Fig. 3 (*g*).

Machine 1 is a constant-speed prime mover. The gear ratios are such that when the main driving shaft of 3 is stationary the armature of machine 2 will rotate at the same speed as the prime mover but in the opposite direction. These conditions apply when the vehicle is standing. Machine 2 is then excited and runs as a generator supplying current to the third unit, which now tends to run as a motor. Thus two torques are applied to the main shaft, (1) that due to machine 3 acting as a motor, and (2) that due to the mechanical reaction, through the gearing, which must exist when the second machine is generating. The speed is increased by weakening the field of 3 and strengthening that of 2. When 2 has been reduced to a very low speed, the field of 3 will be practically zero, so that the armature of machine 2 will virtually be short-circuited by that of machine 3: under these conditions the armature of machine 2 is almost locked, and the torque applied to the main shaft, which now revolves at half the speed of the prime mover, is purely mechanical in its origin. At this point the field of machine 3 is excited so that it acts as a generator driving the second machine as a motor. The excitation is increased until the voltage of 3 has reached that of the battery, when machine 2 is switched on to the battery. Under these circumstances there will not be any relative motion between 1 and 2, and the main shaft will rotate at the same speed as the prime mover. Further increase of speed is obtained by shunt regulation of either or both machines 1 and 2.

With this control the battery current is maintained fairly constant, and regeneration may be obtained.

## THE CHASSIS.

The design of the chassis follows in general the precepts laid down by the builder of the gas truck, attention, of course, being paid to the accessibility of the battery and motors, preference being given to the former.

---

* J. P. KEMP: Patent No. 181432/1922.

† W. H. L. WATSON and R. J. MITCHELL: *ibid.*, p. 125.

* W. H. L. WATSON and R. J. MITCHELL: *ibid.*, p. 129.

The facility with which the electric motor may be attached to the steering wheels has led to the adoption by Continental makers of a 3-wheeled light van, the power being transmitted to the road by a single steering wheel, thus retaining all the advantages of the single-motor drive and at once eliminating the differential gear.

Space does not permit of a detailed description of every type of chassis, and from the electrical point of view they present little interest.

### The Charging System.

The method of charging lead cells, when they were first introduced, was by passing a small current of constant value through them until the charge was complete.

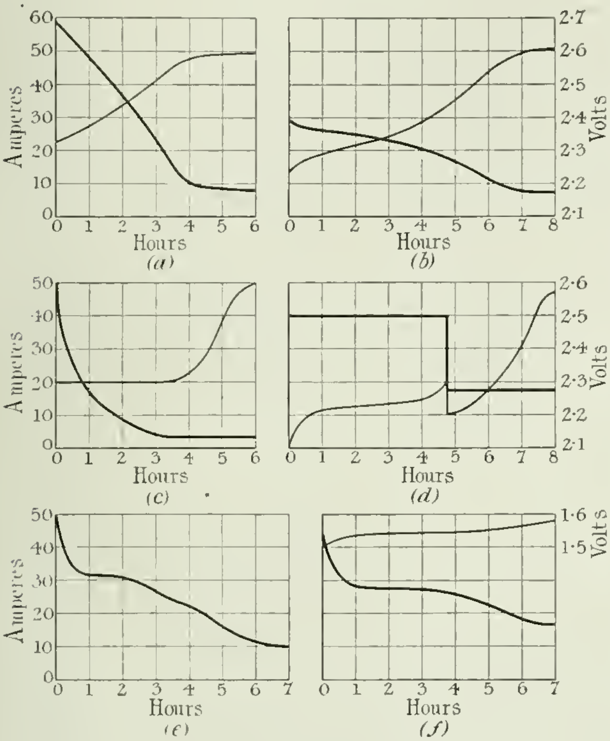


Fig. 4.—Charts showing different methods of charging.

It was found later that, provided a cell did not gas, a heavy charge could be given to it without damaging the plates.

The ideal "gasless" charge is obtained by commencing at a high rate and finishing at a comparatively low rate, and the old method was modified to take advantage of this fact.

In the "tailing" charge, Fig. 4 (*d*), the current is maintained constant at a high value during the first three or four hours (until the voltage reaches 2·3 per cell) and is then reduced to a lower value, at which it is kept until the charge is complete.

In the "constant-voltage" scheme a constant voltage is applied to the battery. The charge proceeds at a very high rate at first, but then falls off to a very low value, this producing two extremes which are not desirable in practice. To overcome these objections the voltage may be applied in two steps. It is important that the supply voltage be very steady, since the current is very sensitive to small variations in the voltage. When the battery is charged from an independent source an automatic regulator may be fitted to adjust this.

Fig. 4 (*c*) shows a chart obtained by a combination of the constant-voltage and constant-current systems.

In another modification of the constant-voltage method a resistance of fixed value is connected in series with the battery. Fig. 4 (*a*) is a charging chart obtained with a series resistance of 0·00535 ohm per cell, and Fig. 4 (*b*) with 0·0166 ohm per cell. It will be noticed that this combination results in a rising voltage and falling current characteristic.

Apart from considerations of efficiency, the fact that the maximum safe current at the end of the charge of a lead cell is comparatively low, limits the practical application of this method to cases where the supply voltage is not in excess of the final battery voltage by more than 75 per cent.

In the series-resistance method a constant line voltage is required, but the resistance exercises a stabilizing influence and the current is not so susceptible to variations in the line voltage.

Automatic charging from a differentially-compounded generator, or from a choked mercury-arc rectifier, presents the simplest method and is practically foolproof. In the case of the latter, at least one set of apparatus is required for every pair of batteries, but it is sometimes found that an installation of small rectifiers, working automatically, is as effective as one large charging generator with its more or less complicated switching and resistances.

In addition to the usual charges, a lead cell requires equalizing about once every two weeks. This charge is given at a very low rate until four consecutive readings, taken hourly, are equal.

The constant-current, constant-voltage, series-resistance, and automatic charging methods are equally applicable to the nickel-iron cell. The constant-current charge is given at the same rate as the normal discharge (5 hour),* and the terminal voltage varies from 1·55 to 1·84 volts.

In the constant-voltage method a voltage of 1·67 volts is maintained at the terminals throughout. The current curve is shown in Fig. 4 (*e*).

When a constant resistance is employed it must be of such a value that it will give a drop of about 0·15 volt when the current is at its normal value. Fig. 4 (*f*) shows a charging curve obtained by this method.

### Boost Charging.

The maximum rate, in amperes, at which a boost can safely be given is approximately equal to the number of ampere-hours (discharge) by which the battery is short of its total capacity. For instance, if the total capacity of the battery is 250 ampere-hours, and it is discharged so that there are only 100 ampere-hours available, the boost-charge rate would be 150 amperes, but this would have to be reduced, as the charge proceeded, in accordance with the above rule. The temperature must not exceed 100° F., and gassing in excess must be avoided.

---

* Charging at a rate lower than normal results in a reduced voltage on discharge. The figures quoted apply to the Edison cell; other makers' figures differ slightly.

The temperature (115° F.) is the only limit to the boosting rate of the nickel-iron cell. The values usually realized in practice are given below.

| Charging rate: Times normal | Period of boost | Volts per cell |
|---|---|---|
| 5 | 5 minutes | 1·92 |
| 4 | 15 ,, | 1·90 |
| 3 | 30 ,, | 1·87 |
| 2 | 60 ,, | 1·83 |

### CHARGING PLANT.

Since the supply voltage is usually too high for direct charging, there arises the problem of providing an economical converting plant.

When the demand is small the partial, or reducing, converter may be used with advantage. The price of the set and the loss involved in running decrease as the ratio of primary to secondary voltage approaches unity.

If the line voltage is approximately an even multiple of the charging voltage a balancer may be used, the three- and five-wire (110/220 and 110/220/440-volt) sets being the most usual type.

When one battery only is to be charged, it is possible to compound the partial converter differentially. With the balancer, however, automatic working of this nature is impossible.

An objection raised against the partial converter and the balancer is that the full line-to-earth voltage may be applied between the cells and earth, and since nearly all battery vehicles are fitted with rubber tyres it is necessary to provide an earth connection in the charging plug to avoid risk of shock.

It is usual to connect an ammeter in the earth circuit at the garage so as to give an indication of the state of the insulation of the cells.

The "dynamotor" is, strictly speaking, a special form of motor-generator, in which it is not possible to regulate the voltage or to compound the generator winding.

This machine has been modified for application to battery charging by fixing the brushes of the "motor" and the "generator" on different axes between which a pair of auxiliary poles are placed. The arrangement is such that by exciting these poles the field in which the motor armature runs is decreased while that in which the generator runs is increased. By this means the difficulties of regulation and compounding are overcome.*

The plant so far considered is suitable for use in connection with d.c. systems only. When the power is taken from an a.c. main the converting machinery takes the form of a motor-generator, rotary converter, or mercury-arc rectifier. Mechanical rectifiers have not yet reached a practical stage except for very small outputs.

When the mercury rectifier is used for battery charging it is necessary to install a starting resistance to act as load during the striking of the arc, for this operation cannot be done when there is a back E.M.F. in the load circuit. As soon as the bulb is working, the battery is put in parallel with the resistance, which is then removed from the circuit.

Rectifiers for battery service are of the glass or quartz type for currents up to 200 amperes, but for larger outputs the now familiar steel construction is adopted.

### CHARGING PANELS.

Charging panels have been developed on the "unit" system and are fitted with a single-pole main switch which has the usual "on" and "off" position and, in addition, a third position into which it may be moved by a slight pressure of the hand. As soon as the pressure is released the switch returns to the normal "on" position.

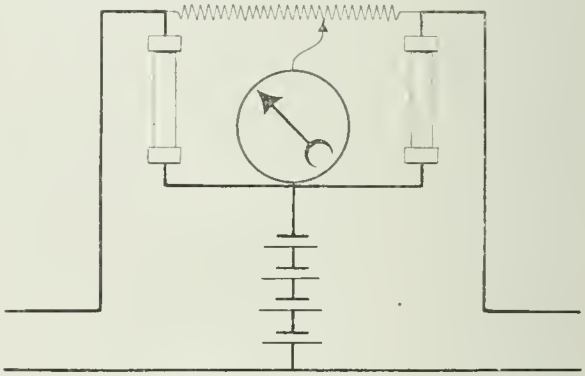


FIG. 5.

The switch is so arranged that when in the third position a voltmeter and an ammeter are brought into the circuit of that particular panel, so enabling the condition of the charge to be noted. This arrangement enables one pair of meters to serve a large number of panels; it saves space and facilitates compact assembly. By this means one set of instruments serves any number of panels. A circuit-breaker with low-current release is provided on the opposite pole. The resistances are brought into circuit by a sliding contact interlocked with the breaker in such a manner that it is impossible to close the latter unless all the resistance is in circuit. Ampere-hour meters are used for indicating the state of the cells and may be fitted with contacts so as to operate a relay on the panel.

The meters are reversible and have a differential shunt winding (Fig. 5) arranged so that when the battery is charging the meter reads low, and, when discharging, reads correctly, thus compensating for the inefficiency of the cell. They may also be compensated so as to allow for the falling-off in the capacity of the battery when on heavy discharge.

---

* Crypto Electrical Co.'s patent.

Meters of this kind are, however, always subject to error, and it is regarded as better practice to use the charging voltage as an indication of the state of the battery. Relay systems can be arranged to operate on this principle.

### CONCLUSION.

In conclusion the author desires to thank the various manufacturers who have so freely assisted him by supplying information and technical data. He wishes to place on record his appreciation of the kindly interest of Mr. L. Brookman of the Chloride Electrical Storage Co., and also of the benefit derived from the many discussions of the subject with Mr. A. W. Evans, who was associated with the paper in its early stages.

## APPENDIX 1.

It is required to compare the losses incurred by speed regulation of a series motor, the increase in speed being effected by reducing the field strength in the following ways :—

(*a*) By arranging the coils in series or parallel.
(*b*) By shunting some of the main current through a resistance.
(*c*) By short-circuiting a portion of the field turns.

The total current is to remain the same in each case.

Let $N$ = number of coils.
$T$ = turns per coil.
$R$ = resistance per coil.
$R_s$ = resistance of the shunt.
$I$ = total current.
$I_c$ = current in each coil.
$I_s$ = current in the shunt.

The normal ampere-turns = $ITN$.

Further, let the reduced ampere-turns be = $kITN$, where $k$ is a constant.

(*a*) In the series-parallel case the turns are constant in value, and the ampere-turns are reduced by paralleling, so reducing the coil current.

Therefore $$I_c = kI$$

Hence, number of parallel branches = $1/k$, and number of coils in series per branch = $kN$, therefore total resistance = $k^2RN$ and total loss = $I^2k^2RN$.

(*b*) In the case of the shunt method, the coils are connected permanently in series so that the ampere-turns must be reduced by diverting some of the current,

therefore $$I_c = kI$$

hence $$I_s = (1 - k)I$$

The resistance of the coils = $RN$,

therefore $$kIRN = (1 - k)IR_s$$

hence $$R_s = \frac{kIRN}{(1 - k)I} = \frac{kRN}{(1 - k)}$$

and the total resistance is

$$\frac{1}{[1/(RN)] + [(1 - k)/(kRN)]} = kRN$$

which gives a total loss = $I^2kRN$.

(*c*) In this case the current in the coils is constant and the reduction of the ampere-turns must be realized by short-circuiting some of the turns themselves.

The number of turns short-circuited = $(1 - k)$.

Total turns left in circuit = $kTN$.

Total resistance left in circuit = $kRN$.

Hence the total loss = $I^2kRN$.

Hence the ratio

$$\text{Loss }(a) : \text{loss }(b) : \text{loss }(c) = I^2k^2RN : I^2kRN : I^2kRN$$

i.e. $$k : 1 : 1$$

And as the field is reduced it is obvious that $k$ must always be less than unity, therefore the loss involved by condition (*a*) is smaller than the losses involved by either of the others.

## APPENDIX 2.

In making a comparison of the characteristics of the various methods of starting, the great obstacle is the absence of a definite law connecting the flux and the excitation.

In the majority of small traction motors the flux between normal load and 300 per cent overload is approximately proportional to the square root of the exciting current. This relation is purely empirical, but the author has found that it is sufficiently accurate to form a basis of comparison.

The following table is based on this assumption.

Further, it is assumed that the drop of volts across the field winding, when normally connected, is 4 per cent and the drop across the armature 4 per cent of the voltage applied to the motor, i.e. the voltage for which it is designed minus the brush-drop, which is approximately constant. These figures apply only when the machine is taking full-load current, and will be subject to an increase or a decrease as the current varies.

The total current is the same in each case.

The connection of the armatures in series will introduce a small additional brush-drop into the circuit and thus reduce the speed a little below the value given.

In the table the following symbols are used :—

$E$ = terminal voltage − brush-drop (constant).
$I$ = total current (constant).
$k$, $k'$, $k''$ = constants.

| | | Normal | Intermediate | Intermediate | Start |
|---|---|---|---|---|---|
| Type of Control | Series-parallel field with double wound armature | 2 Armatures in parallel<br>2 Fields in parallel | 2 Armatures in series<br>2 Fields in parallel | 2 Armatures in parallel<br>2 Fields in series | 2 Armatures in series<br>2 Fields in series |
| | Series-parallel motors | 2 Motors in parallel | — | — | 2 Motors in series |
| | Series-parallel fields | 2 Fields in parallel with one armature | — | 2 Fields in series with one armature | — |
| Flux .. .. | | $\frac{k\sqrt{I}}{\sqrt{2}}$ | $\frac{k\sqrt{I}}{\sqrt{2}}$ | $k\sqrt{I}$ | $k\sqrt{I}$ |
| " Drop " in volts .. | | $0{\cdot}04E + 0{\cdot}04E$ | $0{\cdot}16E + 0{\cdot}04E$ | $0{\cdot}04E + 0{\cdot}16E$ | $0{\cdot}16E + 0{\cdot}16E$ |
| Speed .. .. | | $\frac{k'(E-0{\cdot}04E-0{\cdot}04E)\sqrt{2}}{\sqrt{I}}$ | $\frac{\frac{1}{2}k'(E-0{\cdot}16E-0{\cdot}04E)\sqrt{2}}{\sqrt{I}}$ | $\frac{k'(E-0{\cdot}04E-0{\cdot}16E)}{\sqrt{I}}$ | $\frac{\frac{1}{2}k'(E-0{\cdot}16E-0{\cdot}16E)}{\sqrt{I}}$ |
| $\frac{\text{Starting speed}}{\text{Normal speed}}$ | | — | 0·435 | 0·615 | 0·261 |
| Torque .. .. | | $\frac{k''\sqrt{I}\times I}{2\sqrt{2}}$ | $\frac{k''\sqrt{I}\times I}{\sqrt{2}}$ | $\frac{k''\sqrt{I}\times I}{2}$ | $k''\sqrt{I}\times I$ |
| $\frac{\text{Starting torque}}{\text{Normal torque}}$ | | — | 2 | 1·41 | 2·82 |

# STEAM TURBINE BLADING.

By J. C. READ, B.Sc., Student.

(ABSTRACT *of paper read before the* LONDON STUDENTS' SECTION, 24*th November*, 1922.)

SUMMARY.

The paper is a review of the present position of the subject of steam turbine blading.

Section (1) describes the causes and effects of corrosion and erosion. The most important materials in use are enumerated and compared.

Section (2) deals with the form of the blade passage in impulse and reaction machines, and with the energy losses occurring in the blading. Some methods of tapering the blades are given.

Section (3) details the stresses in the blades and describes the types of blade fastenings, lacing and shrouding.

Section (4) gives the methods used for obtaining a large exhaust area.

Section (5) deals with vibration and its causes, and shows a method of correcting for the effect of centrifugal force. The lines on which the problem is being attacked are described.

Section (6) is devoted to the methods of manufacture by milling and by drop forging.

A bibliography is appended.

## INTRODUCTION.

The whole future of the electrical industry in this country is becoming so dependent on steam-turbine development that it seems desirable for electrical engineers to have some knowledge of the details of turbine design. Of these details the blading is one of the most important, since it affects very directly alike the reliability, the efficiency, and the initial cost of the machine, and at the same time is a limiting factor in designs for large outputs and high speeds. It is at present the subject of special research by the B.E.A.M.A. This paper is an attempt to review the position as it now stands.

## (1) MATERIALS.

The main causes of the deterioration of blades in service are corrosion and erosion, and may be classed as follows:—

(1) *Corrosion.*

(*a*) Chemical action of high-temperature steam on the metal. This trouble is peculiar to aluminium bronze at temperatures above 200° C. The aluminium gradually disappears from the surface, leaving a layer of very brittle copper which soon flakes off.

(*b*) Chemical corrosion due to impurities in the steam. This is mainly due to the acid vapours formed at high temperatures from calcium or magnesium chloride in the make-up water. Faulty condensers, which permit the penetration of sea water, mine water, sewage, etc., are also a frequent cause of corrosion.

Chemical corrosion and rusting can be appreciably reduced by the occasional injection of a small quantity of kerosene into the steam supply.

(*c*) Rusting occurs to some extent during running, chiefly due to the air dissolved in the feed water. It can be largely prevented by eliminating as far as possible any contact of the feed water with the atmosphere during its cycle.

(*d*) Rusting while standing idle is due to steam leaking into the turbine past the stop valve, and may cause serious damage. Such leakage may be best prevented by the provision of two stop valves in series, with provision for any steam that leaks past the first to escape to the open air; and it is also important to dry the turbine out thoroughly after use.

(2) *Erosion.*

(*a*) Erosion by wet steam produces a scoring of the back (convex side) of the moving blades at the entrance edge. The majority of the water does not travel suspended in the steam, but collects as a film on the concave face of the fixed blades or nozzles, from which it drips, and is thus struck by the backs of the moving blades, producing the characteristic erosion on the latter. This trouble can be greatly reduced by efficient draining from every stage.

(*b*) The worst form of erosion is that produced by boiler dust. The damage occurs on the front (concave side) of the blade, and may be easily recognized. The dust is formed in the superheater from the mud carried over when the boiler primes, and hence any mud traps, to be effective, must be inserted between the boiler and the superheater.

When the steam has been expanded down to saturation in the turbine, the dust is re-converted into mud and deposited in the low-pressure blading, which gradually becomes choked up. Under special conditions sudden choking up may occur when the boiler foams badly or boils over, such foaming being generally due to the presence of soda or salt in the water.

(*c*) An appreciable part of the erosion of the low-pressure blades may also be attributed to metallic particles dislodged from preceding stages.

The ability to withstand corrosion and erosion is one of the principal attributes required in a blading material. In addition, the material should be mechanically strong, and should maintain its strength well at high temperatures; it should be reasonably cheap and easy to machine; and above all it must be thoroughly reliable. The lack of a material which can satisfactorily fulfil these conditions has long been a serious difficulty. As a consequence there is no uniformity of practice in this respect, and many different metals are employed.

*Brass and copper.*—These metals withstand corrosion well and are easy to machine. At medium temperatures they become plastic. Brass is suitable for use, where the stresses are low, up to about 200° C. for blades and 250° C. for spacers.

*Phosphor-bronze.*—This metal possesses the great advantage of being somewhat more dependable than many of the newer alloys. It cannot be used in the first stages, since its strength falls considerably at high temperatures, but it is highly suitable for the middle part of the machine, where the temperature and stresses are both moderate. It is readily machined or drawn to shape, and is fairly free from corrosion. The tensile strength when cold is 20 to 24 tons per square inch, with a yield point of about 12 tons per square inch.

*Monel metal.*—This usually consists approximately of Ni 67 per cent, Cu 29 per cent, Fe 3 per cent and Mn 1 per cent, and is the most promising of the non-ferrous alloys. It has an unusually high tensile strength of about 45 tons per square inch, which is remarkably well maintained at high temperatures, and it can be both forged and machined. It is expensive, but it is of great value where acidic steam is to be expected. There are some difficulties in obtaining supplies of uniform composition.

25 *per cent nickel steel.*—This was used at one time, as it was supposed to be non-corrodible. It is completely unreliable.

3–5 *per cent nickel steel and mild steel.*—These are both now widely used. The nickel steel has a slightly higher tensile strength, amounting to 36 to 40 tons per square inch, with 5 per cent of nickel, but it occasionally gives trouble by developing quenching cracks. The two steels rust equally, but by sherardizing and by the other precautions which have been mentioned the rusting can be reduced to a small amount.

*Alloy steels.*—Alloys such as chrome-nickel steel and nickel-chrome-vanadium steel have been largely used in America for the sake of their high tensile strength. They have not proved an entire success.

*Stainless steel.*—This metal, discovered by Mr. H. Brearley in 1912, contains 12 to 14 per cent of Cr and about 0·3 per cent of C. It can be produced in three forms, annealed, tempered, and hardened, of which only the tempered variety is of use for blading. In that state it can be machined, though with difficulty; it has a tensile strength of about 50 tons per square inch, which is fairly well maintained at high temperatures, and these factors, combined with its freedom from corrosion, render it an ideal material for steam turbine blading. Unfortunately it is very sensitive to heat treatment, and this has led to some difficulties in the past; but if special care is taken in its manufacture and testing it is probable that satisfactory results will be obtained. The benefits to be hoped for from this metal are very great.

To sum up, the favourite material for impulse machines at the present time is 3 to 5 per cent nickel steel in this country, the principal exception to the rule being the British Thomson-Houston Co., who have abandoned this metal and employ sherardized mild steel for blades subjected to high temperatures or high stresses, and phosphor-bronze for the remainder. In reaction machines brass is still in common use except for the largest blades. In America, monel metal and various alloy steels are in favour.

### (2) THERMODYNAMIC DESIGN OF BLADES.

Reaction-blade passages take the form of a convergent nozzle with the entrance angle disposed to absorb the leaving velocity from the previous stage without undue shock. The forms of the blades used have been fixed empirically from the results of experiments. Since expansion takes place both in the fixed and moving elements, identical blades are used in the rotor and casing; the pitch, however, is usually slightly greater in the casing than in the rotor.

It is very difficult to determine what is the real internal efficiency of reaction blading. Martin estimates it as 90 per cent for velocities of 200 to 300 ft. per sec. The losses due to curvature are probably much lower than in the impulse turbine, owing to the lower steam velocity. The efficiency could be appreciably increased by increasing the ratio of blade speed to steam speed, and thus causing the blades to develop more of their power by reaction and less by impulse, as in the Ljungström machine.

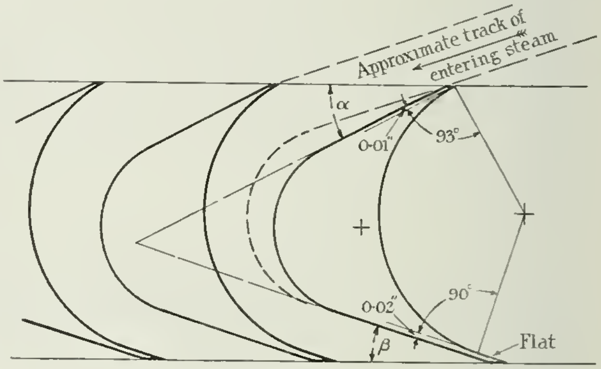


FIG. 1.

The blade passage in impulse turbines appears at first sight also to take the form of a convergent nozzle, as shown in Fig. 1. Actually it behaves almost as if there were no convergence, the reasons being that the steam does not enter tangentially to the blade surface, and that the high jet velocity causes the steam to bank up on the concave face and only partially " fill " the channel. Experiments by Rateau have shown that the fact that the jet does not enter tangentially causes no appreciable loss up to an angle of obliquity of about 25°; on the other hand, the large entrance angle is advantageous since it reduces the tendency of the steam to strike the backs of the blades at light loads.

The shrouding, now always fitted, is of considerable importance in preventing losses, as well as in steadying the blades. It serves to prevent the steam from spreading out radially, and also eliminates the disturbing effect of the casing on the steam flow.

The losses occurring in impulse blade channels may be conveniently grouped as follows :—

(*a*) Losses by shock wherever abrupt decreases of steam velocity take place, notably in velocity-compounded stages.

(*b*) Losses by shock when partial admission is used, where the steam from the first of the nozzles impinges on the dead steam in the blade channel.

(*c*) Friction and eddy losses where the band of steam flowing between the nozzles and the blades cuts across the edge of the zone of dead steam in the clearance space.

(*d*) Friction losses in the blade passage. These are generally small, but they are of importance because they limit the minimum blade height and maximum axial width permissible. The blade faces are usually polished, partly in order to reduce the friction losses to a minimum.

(*e*) Eddies in the blade passage, which constitute the main source of loss. According to Loliger, these take the form of a double corkscrew whirl, in which steam flows along the concave blade face from the middle to the two ends, and returns to the middle along the convex face. The eddy losses increase rapidly with the steam speed and with the total angle of curvature, and decrease with increasing radius of curvature.

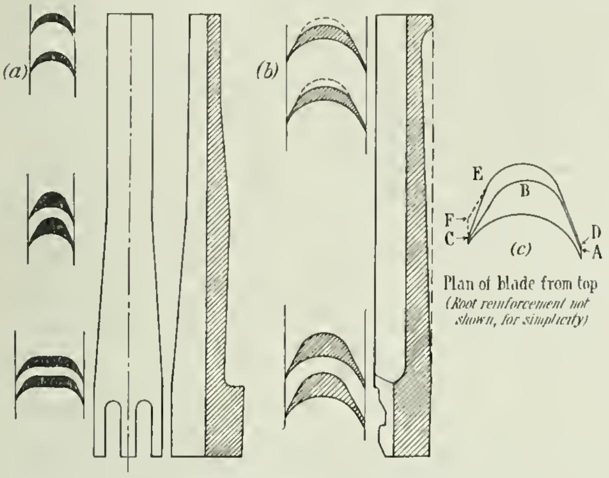


Fig. 2.

(*a*) Blade tapered in width and thickness (Baumann's method).
(*b*) Blade tapered by thinning back.
(*c*) Blade tapered in thickness, with varying inlet angle to conform with varying angle of entrance of steam.

Published figures are lacking as to the effect of the pitch on the efficiency. Fig. 2 illustrates a few methods used for tapering blades. The first aims at a constant breadth of steam passage at the expense of great axial width ; the second gives insufficient guidance to the steam near the tip ; while the third possesses the special advantage of giving a varying entrance angle to conform with the varying angle at which the steam impinges on the blade. In this latter case, a first cut along the back produces the profile tapering from ABC at the tip to DEF at the root, and a second cut clears away the tetrahedral piece CEF.

It is usual to take account of the whole of the losses in the buckets by a coefficient $\psi$, known as the velocity coefficient, which is equal to the ratio of the actual leaving velocity to the theoretical leaving velocity. Published values of $\psi$ for impulse blades lie between 0·75 and 0·88.

### (3) Mechanical Design of Blades.

The direct tensile stress in the root of a parallel blade is :—

$$f_t = \frac{Wh\omega^2 D}{2g} = \frac{2Whu^2}{gD} \quad . \quad . \quad . \quad . \quad (1)$$

where $f_t$ = tensile stress ;
$W$ = weight of blade material per unit volume ;
$u$ = mean peripheral speed of blades ;
$D$ = mean diameter of blade circle ;
$\omega$ = rotational speed, in radians per sec. ; and
$h$ = blade height.

The stress in the blade fastening will, of course, generally be higher, in a proportion depending on the individual type of fastening employed. The stress can be reduced without reducing the blade height, by tapering the blade as has been described.

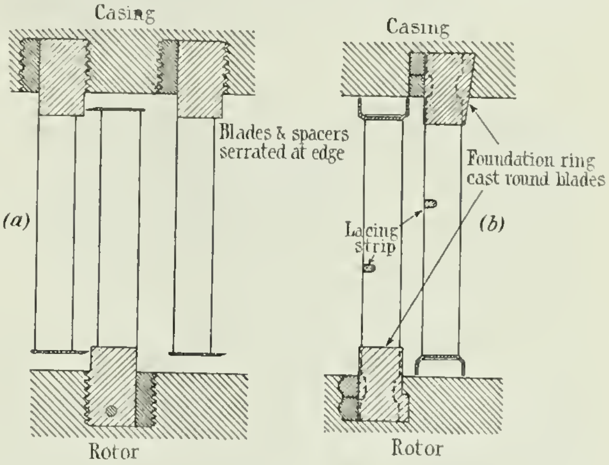

Casing
Casing
Blades & spacers serrated at edge
Foundation ring cast round blades
(a)
Lacing strip
(b)
Rotor
Rotor

Fig. 3.

(*a*) Parsons "lock-root" blade fastening.
(*b*) Allis-Chalmers blade fastening.

The highest value of $u$ used is in the de Laval machines, where it reaches 1 300 ft. per sec. In large impulse machines 800 ft. per sec. is about the limit ; in Parsons machines it never exceeds 650 ft. per sec.

Superposed on $f_t$ is the bending stress due to the torque on the blade. This stress, which can be easily calculated, does not usually exceed 20 to 25 per cent of $f_t$. It is noticeable, however, that the crescent-shaped section of turbine blades is particularly weak to resist these bending stresses, since all the stresses reach their maximum at the edge of the blade, which, owing to its thinness, is most likely to contain incipient flaws.

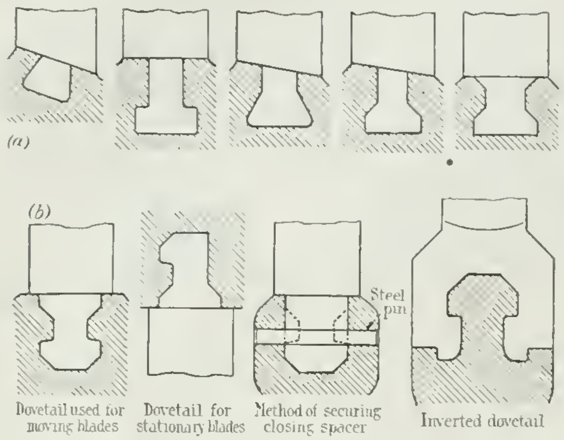
The factors of safety used vary from 2 to 3·5, referred to the yield point.

The old methods of securing the blades of reaction machines by caulking have now been abandoned, and a positive mechanical system of fixing is now always employed. Two typical methods are illustrated in Fig. 3.

The three principal fastenings now employed in impulse machines are the riveted type introduced by Rateau and used in Metropolitan-Vickers and Fraser and Chalmers machines, the dovetail type, and the inverted dovetail. There appears to be little to choose between the first two of these, for medium stresses. Where great strength is required the inverted dovetail is substituted for the simple dovetail.

The steps by which the present usual form of dovetail was evolved by two separate firms can be seen in Figs. 4 and 5.

Fig. 5 shows the development of the A.E.G. blade fastening. The original A.E.G. design was the simplest possible, as shown in (*a*). The high local stress which this obviously entails was next reduced by a counter dovetail, as in (*b*). The next step, in which the construction was stiffened by the use of super-elevated spacers, is shown at (*c*). Tests on this design showed that the strength could be greatly increased by rounding the corner of the dovetail, as in (*d*), and a further slight gain was obtained by the modification shown in (*e*). The next stage was to cut away the edges near the root, as in (*f*), in order to reduce the high stresses and liability to corrosion at these points. To obtain greater strength it then became necessary to reinforce the root section, as shown in (*g*). The greatest weakness now lay in the high compressive stress in the root, and (*h*) shows the hammer-head form which was adopted to avoid this fault, (*i*), (*j*) and (*k*) showing the steps whereby this design was developed. Finally the reinforcing of the root was extended to eliminate the spacer altogether, and thus the design (*l*) was obtained.



Dovetail used for moving blades Dovetail for stationary blades Method of securing closing spacer Inverted dovetail

FIG. 4.

(*a*) Early types of B.T.H. blade fastenings.
(*b*) Modern types of B.T.H. blade fastenings.

Fig. 4 shows the modern British Thomson-Houston dovetail and a number of older designs. The similarity between the two processes of evolution is evident.

In reaction machines, vibration of the blades is prevented by one or more lacing strips threaded through them at the entrance edge, and usually secured by silver soldering. Lacing wires and distance pieces at intermediate points along the blade are also used in impulse turbines to prevent vibration. Their use is generally avoided, however, because with the higher steam speeds employed these devices set up excessive eddies.

Shrouding is now fitted in both impulse and reaction machines. In Parsons machines the use of fine radial clearances has been abandoned, and a fine axial clearance at the edge of the shrouding is employed instead.

Reaction blading, which is too thin to permit riveting, usually has the shrouding silver-soldered or brazed on to it. Impulse shrouding is almost invariably riveted. A considerable increase of lateral rigidity might be expected if the shrouding were brazed in addition to being riveted.

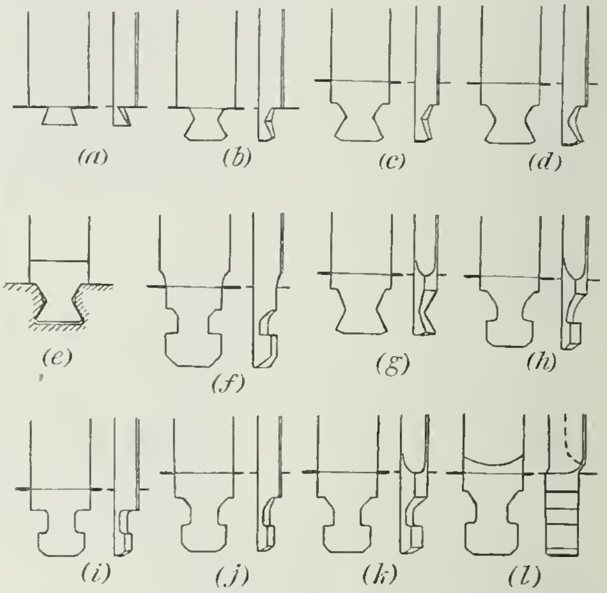


FIG. 5.

### (4) EXHAUST AREA.

The need for a large projected blade area in the last stage is due to the necessity of reducing to as low a value as possible the loss due to the residual kinetic energy of the steam leaving the turbine.

From Equation (1), since the projected blade area is $A = \pi D h$, it follows that

$$A = \frac{2\pi g f_t}{W\omega^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

whence it is clear that it is immaterial to the stress in the blade roots whether the exhaust area is obtained with a large diameter and short blades or with a small diameter and long blades.

For machines of very large power operating at high vacua it is necessary to employ special means to obtain this large area. The principal methods are :—

(*a*) The construction of the low-pressure portion of the turbine on the double-flow principle.

(*b*) The provision of two wheels in parallel for the last stage (only possible in few-stage turbines).

(*c*) The use of multi-exhaust blading. The last method, which is that most directly connected with blade design, is fully discussed in Mr. Baumann's recent paper.*

### (5) VIBRATION.

The possibility of failures due to fatigue caused by vibration has recently become of great importance, and is now the chief limiting feature in large steam turbine design.

The intricacy of this problem lies in the fact that there is no known way of predicting what the natural frequency of the disc and its blades will be. Further, so little is known of the relative potency of the factors influencing this natural frequency, which, moreover, is difficult to measure even in a finished machine, that even experimental data are scarce and very limited in their application.

The factors which are known to influence the natural frequency are :—

(*a*) The shape of the disc and its blades, the effect of which is calculable.

(*b*) The speed of rotation, since the natural frequency is greatly increased by the stiffening action of the centrifugal forces. Due to this, test-results obtained on a wheel at rest are not valid when the wheel is rotating, but the necessary correction can be calculated under certain conditions.†

(*c*) The pressure of the steam in which the wheel is rotating.

(*d*) The temperature distribution in the wheel, the natural frequency being generally lowered by uneven distribution.

(*e*) The forging stresses in the disc.

(*f*) External influences, such as those from the propeller in geared ship's turbines.

(*g*) The type of vibration, which may take any of a number of moderately complicated forms.

The principal methods by which the vibration problem is being attacked may be roughly grouped under six heads.

(i) *The use of high-speed turbines.*—These use smaller and thicker discs than the low-speed machines, so that the natural frequency of the discs is further removed from the running speed. On the other hand this brings the natural frequency of the blades nearer to the running speed, but as this can be more nearly predicted than that of the disc the net result is a gain, especially in view of the fact that a disc failure would in any case be much more disastrous than a blade failure.

(ii) *The use of specially thick discs.*—It has been found that a stiff rim is of great importance in reducing vibrations. A large factor in causing the failure of the turbines which have failed through disc vibration was the use of an unduly light rim, which had been occasioned by the substitution of the inverted-dovetail blade fastening for the ordinary dovetail. The rims used with inverted dovetails now have a heavier rib formed in the disc just below the blade fastening.

The method used in some recent Metropolitan-Vickers machines to obtain stiffness is specially interesting. The blade length is much increased, and the size of the disc is correspondingly reduced until it is little more than a collar on the shaft. To obtain sufficient strength to resist centrifugal force the disc is actually riveted to the shaft, and is split diametrally to enable it to be assembled.

(iii) *Vibration tests on running turbines.*—These are difficult to carry out, since the apparatus has to be built into the turbine.

(iv) *Tests on vibration of wheels and blades at rest.*—Various methods have been proposed, the general principle being to mount the rotor on some flexible support and then subject it to mechanical vibration of known frequency.

(v) *Experiments with models*, with a view to throwing light on the factors influencing vibration.

(vi) *Research on fatigue*, especially on the behaviour of metals subjected to extremely high numbers of stress reversals.

From Gilchrist's theory of fatigue failure it follows that the principal conditions for resistance to fatigue are :—

(*a*) The metal should be homogeneous, being as free as possible from cracks, flaws and impurities.

(*b*) The design should be such as to avoid any high local stresses caused by sharp corners, etc.

(*c*) A high surface finish considerably increases the resistance to fatigue failure.

### (6) METHODS OF MANUFACTURE.

The spacers between the blade roots, where used, are milled from rolled or extruded bar, which may be either of the same cross-section as the dovetail, or of the crescent-shaped cross-section of the space between the back of one blade root and the front of the next.

Reaction blades and many low-stressed impulse blades in which the root is not reinforced, are made by simply extruding or drawing the metal to the finished profile, and only doing such machining as is necessary for forming the dovetail, receiving the lacing strip, etc.

Another inexpensive method is to stamp the blade from sheet metal and then bend it to the desired curvature. As this gives a blade of constant thickness, which is recognized as an inefficient form, it is now customary, where this system is employed, to follow the bending by a cut along the back with a profiling cutter.

For larger blades with reinforced roots the usual procedure is to mill the blade out of solid bar, generally of rhubarb section. The concave face is always milled in a longitudinal direction along the blade by a profile cutter, and this is also the quickest and most accurate method of machining the back. In a few cases the back is milled in a special revolving jig by a cutter having its axis parallel to the blade. This has the advantage of enabling the correct profile of the back to be carried well down to the root, which is not possible with the other method.

---

* K. BAUMANN: "Some recent developments in large steam turbine practice," *Journal I.E.E.*, 1921, vol. 59, p. 565.

† A method for the blades is described in the original paper.

A combination of the two processes is often employed and probably offers the best solution. The following sequence of operations may be taken as being fairly typical. Having been cut roughly to length, the blade is milled along the back by a profiling cutter, after which the shape of the back is continued down to the root by the revolving jig method. The sides are next milled to give the blade the correct width, and the dovetail is then cut in the root by means of two cutters of the correct shape set with their axes parallel and the necessary distance apart. The next operation is to mill out the concave face, the profile of which is continued down to the root by means of a special end-milling cutter. The tenon to receive the shrouding is then milled on the top, a finishing cut is taken along the bottom, and the process is completed by filing off the burrs and polishing or sherardizing, according to whether the blade is of phosphor-bronze or mild steel.

Blades having inverted-dovetail roots have to be made from rectangular bar, in which case the quantity of metal to be machined off the back is very considerable. It then pays to mount the blanks in pairs face to face in a lathe and turn off the bulk of the metal, so as to reduce the amount of milling to be done on the back of the blades.

The large amount of machining necessary with the inverted-dovetailed blades has led in America to the adoption of drop forging for these blades, the root being generally finished by milling. This is specially advantageous when alloy steels are used, since the cost of machining increases rapidly for tensile strengths above 50 tons per sq. in. In this country drop forging is scarcely ever employed, its disadvantages being the reduction of the strength of the blades, together with the high cost and short life of the dies.

With monel metal, using a single blow, a die will forge about 5 000 blades before requiring repair, but when steel blades are used the life of the die is far shorter.

The accuracy obtainable with drop-forged blades is practically equal to that obtainable by milling. By the use of very special care, limits of ± 0·002 in. can be obtained with milled blades, but the average results are not much better than those obtained by drop forging; e.g., the Bethlehem Shipbuilding Corporation allow tolerances of + 0·006 in. and − 0·004 in., or $1\frac{1}{2}°$ in angles, in drop-forged monel blades having edges 0·020 in. thick.

### CONCLUSION.

In conclusion the author wishes to acknowledge his indebtedness to the following firms who very generously gave him assistance and information: The British Thomson-Houston Co., Ltd.; Messrs. C. A. Parsons and Co., Ltd.; The Metropolitan-Vickers Electrical Co., Ltd.; Messrs. Greenwood and Batley, Ltd.; The English Electric Co., Ltd.; The Brush Electrical Engineering Co., Ltd.; Thos. Firth and Sons, Ltd.; Thos. Bolton and Sons, Ltd.; Messrs. Bruntons, Ltd.; Brown, Boveri and Co., Ltd.; Escher, Wyss, et Cie; Société Alsacienne de Constructions Mécaniques; Schneider et Cie; Société de Mécanique Rotative; Société Rateau; Bethlehem Shipbuilding Corporation, Ltd.; Ridgway Dynamo and Engine Co.; Kerr Turbine Co.; and Allis-Chalmers Manufacturing Co.

### BIBLIOGRAPHY (ABRIDGED).

1. RATEAU: "A Method of Calculating Steam Turbines," *Association Technique Maritime*, Paris; and *Engineering*, 1909, vol. 88, p. 804.
2. N. BRILING: "Energy Losses in Steam Turbine Buckets," *Zeitschrift des Vereines deutscher Ingenieure*, 1910, vol. 54, pt. 1, pp. 265, 352, 389 and 474, and *Engineering*, 1910, vol. 89, p. 552.
3. G. STONEY: "Stresses in Turbine Blading," *Engineering*, 1918, vol. 105, p. 447.
4. W. B. PARKER: "Specifications for Alloys for High-Speed Superheated Steam Turbine Blading," *Engineering*, 1915, vol. 100, p. 307.
5. A. FENWICK: "Deterioration of Steam Turbine Blading," *Engineering*, 1917, vol. 103, pp. 419 and 471.
6. D. F. DUCEY: "Low-Pressure Turbine Blading Failures," *Journal of the American Society of Naval Engineers*, 1921, vol. 33, p. 512, and *Engineering*, 1921, vol. 112, p. 647.
7. W. F. RICE: "Monel Metal Blades in Destroyer Turbines," *Power*, 1920, vol. 51, p. 908.
8. W. J. GOUDIE: "Steam Turbines." [Longmans, Green, 1922.]
9. K. BAUMANN: "Some Recent Developments in Large Steam Turbine Practice," *Journal I.E.E.*, 1921, vol. 59, p. 565.
10. "Stainless Steel," *Iron and Coal Trades Review*, 1921, vol. 103, p. 626.
11. O. LASCHE: "Erfahrungen an der Beschauflung von Dampfturbinen Laufraedern," *Zeitschrift des Vereines deutscher Ingenieure*, 1918, vol. 62, p. 583.
12. "Les Vibrations d'Aubes dans les Turbines à Vapeur; Influence de la Force Centrifuge sur la Periode Propre," *Revue Brown, Boveri et Cie.*, Oct., 1920, p. 267.

# TEMPERATURE MEASUREMENT WITH THE EINTHOVEN GALVANOMETER.

By F. ADCOCK, Ph.D., and E. H. WELLS, Ph.D., Students.

(ABSTRACT *of paper read before the* SOUTH MIDLAND STUDENTS' SECTION, *23rd March*, 1923.)

### SUMMARY.

Accurate measurement of instantaneous temperatures during a cycle of variation is of great importance in the application of the theory of thermodynamics. In the past, temperatures of the working charge in the internal-combustion engine have been deduced from a conditional equation for the gas, values obtained by measurement and estimation being assigned to the other variables in the equation. Serious errors of unknown magnitude may be involved in such estimation, and the deduced temperatures are liable to corresponding inaccuracies.

Thermo-couples and platinum-resistance thermometers have been used by a number of experimenters for obtaining records of the cyclically varying temperature, but these records do not directly give the temperature of the charge, even if they represent accurately the temperature of the thermometer.

The object of the work undertaken is the investigation of the relationship between the temperature of the gas in which the thermometer is situated and the thermometric record obtained.

Attention has been devoted primarily to the platinum-resistance thermometer. As it is required to obtain a continuous record of temperature throughout a single cycle, the method adopted is to measure the out-of-balance current in the Wheatstone bridge by means of an Einthoven galvanometer.

The forces on the fibre of the Einthoven galvanometer are considered, and the suitability of various types of fibre are compared.

The mathematical theory of the unbalanced Wheatstone bridge is investigated. The general case is considered, and alternative arrangements are compared with respect to sensitivity and error in compensation. An estimate of the accuracy with which the galvanometer deflection corresponds to the temperature attained by the measuring wire is given.

The apparatus designed to investigate the problem is described, and experimental results are given and discussed.

### INTRODUCTION.

The measurement of varying temperatures is a problem which holds the interest of engineers just as the measurement of other varying quantities such as displacement, velocity and pressure, have claimed and are claiming their attention. Attention to the question of measurement of varying temperature is sharply focused by the search for improved economy in internal-combustion engines.

A considerable amount of work on the subject of varying temperature measurement has been done, and the names of Burstall, Hopkinson, Callendar and Dalby, Coker and Scoble, Nagel, Petersen, and Wolff stand out prominently.

An instrument which was devised primarily for recording the continuous changes of potential difference accompanying the beating of the heart, the Einthoven galvanometer, has been pressed into service for recording continuous changes of temperature.

Two electrical methods of measuring temperature are available: first the thermo-couple method which depends on the E.M.F. set up when the two junctions of dissimilar metals are at different temperatures; and secondly, the resistance-thermometer method which depends on the change of resistance of a conductor when its temperature changes. In the latter case, by connecting the conductor of changing resistance in a Wheatstone bridge, corresponding changes of potential difference are produced across the galvanometer and these are utilized for determining the temperature.

In order that the current in a galvanometer shall be able accurately to follow rapid changes in E.M.F. at its terminals, its coefficient of self-induction must be small; and in order that the deflection shall be able to follow the changes in the current, the inertia of the moving parts must be small. One of the most satisfactory of all types of galvanometer is the moving-coil type, but the ordinary laboratory instrument has a large number of turns in the coil and therefore considerable inertia and self-induction. A mirror forming part of the moving system also adds to the inertia.

### THE EINTHOVEN GALVANOMETER.

Both inertia and self-induction are reduced to a minimum in the Einthoven galvanometer, in which the coil is reduced to a single conducting fibre and the mirror is dispensed with altogether, the deflection of the middle of the fibre being observed by means of its shadow cast on a screen or photographic plate while its ends are held stationary.

When working with the Einthoven galvanometer it is necessary to know the following characteristics of each fibre used :—

(1) Resistance.
(2) Calibration of scale reading against difference of potential.
(3) Natural frequency of oscillation.
(4) Time taken to attain final deflection after suddenly switching on or off.
(5) Effect on (2), (3) and (4) of altering the setting of the tension screw.
(6) Effect on (1), (2), (3) and (4) of change in temperature.

In connection with (3) above, whether the galvanometer is dead-beat or not depends on the amount of damping present, and this varies with the resistance of the external circuit through which induced currents flow. Experiments show that when the galvanometer is connected in the Wheatstone bridge, the effective resistance of the induced-current path is sufficiently low to make the galvanometer dead-beat, but on open circuit, when the only damping is by air friction, it is not.

If $f$ denote the tensile stress in dynes per $cm^2$,
$s$ the density in grammes per $cm^3$ of the material of the string,
$l$ the length of the string in cm, and
$n$ the natural frequency in periods per second,
then it can be proved that

$$n = \frac{1}{2l}\sqrt{\frac{f}{s}}$$

that is, the frequency is independent of the diameter and modulus of elasticity of the string.

From this formula, the frequency can be calculated for fibres of different materials in terms of the tensile stress and density.

The materials of which fibres are made for use in the Einthoven galvanometer are glass, copper, aluminium and silver. The glass fibres are coated with silver in order to give them conductivity, but this silver, when the coating is thin, increases the weight only slightly and does not add anything to the mechanical strength, and in this connection it has been neglected. The length of the Einthoven fibre is nominally 10 cm and the following table is calculated for this value.

| Tensile stress | | Natural frequency per second | | |
|---|---|---|---|---|
| Dynes per $cm^2$ | Tons per sq. in. | Glass or aluminium ($s = 2·7$) | Copper ($s = 8·9$) | Silver ($s = 10·5$) |
| 12·4 | 8 | 1 070 | 590 | 544 |
| 6·2 | 4 | 760 | 418 | 384 |
| 3·1 | 2 | 536 | 295 | 272 |
| 1·55 | 1 | 379 | 208 | 192 |
| 0·775 | 0·5 | 268 | 147 | 136 |
| 0 | 0 | 0 | 0 | 0 |

This formula has been used to calculate the tension from the observed frequency, and thus to determine the maximum safe tension which may be applied to the fibre.

The maximum frequency obtainable is obviously less than the value obtained by putting $f$ equal to the ultimate strength of the material. This value is shown in the following table :—

| Material | Ultimate strength, tons per sq. in. | Frequency corresponding to ultimate strength |
|---|---|---|
| | | p.p.s. |
| Glass .. .. .. | 1·9 | 520 |
| Silver .. .. .. | 19 | 840 |
| Copper .. .. | 26 | 1 060 |
| Aluminium .. .. | 11 | 1 270 |

From considerations of frequency it appears that aluminium is by far the best material to use, but so far it has not been possible to draw a wire finer than 0·035 mm diameter and this has a resistance of about 7 ohms, so that in cases where a higher resistance than this is required aluminium cannot be used.

The fourth characteristic (time taken to attain final deflection) is best determined experimentally. When a difference of potential is switched on, the fibre is in the condition of a short-circuited coil in a magnetic field and is brought to rest by induced currents. When a difference of potential is switched off and the galvanometer is put on open circuit the fibre is not brought to rest so quickly. Under the conditions adopted for these experiments the times taken to come to rest were 0·01 sec. and 0·1 sec. respectively.

### THE OBJECT OF THE PRESENT WORK.

The Einthoven galvanometer has been used by a number of investigators for the purpose of determining temperatures in the gas-engine cylinder, and their work clearly shows the practicability of recording quantitative results for the cycle of temperature in the heat-engine cylinder.

In order that the results recorded may be interpreted in terms of the temperature of the gas itself, it is necessary to know the relationship between the true temperature and the temperature assumed by the thermometer. It is the object of this research to investigate this relationship.

The difference between the temperature assumed by the thermometer and the temperature of the gas at any instant, which may be termed the " temperature lag," will depend mainly on the following points, the effects of which require investigation :—

(1) The form of the thermometer employed.
(2) The rate of variation of temperature of the gas.
(3) The nature and temperature of the walls of the containing vessel.
(4) The velocity of gas relative to the thermometer.

It is intended that the thermometer which will be employed in the gas engine shall be of the type used in Prof. Burstall's earlier work, i.e. the platinum-resistance thermometer. The investigation, therefore, refers primarily to the platinum-resistance thermometer, and apparatus has been designed and constructed accordingly.

The scheme adopted consists of maintaining steady temperatures of different intensity in different regions, and moving the thermometer through these regions to obtain the cyclical variation of temperature ; the rate of variation of temperature is determined by the frequency of movement of the thermometer through the different temperature regions.

In the design of the experimental thermometer it was necessary to provide as closely as possible for the fulfilment of the following conditions :—

(*a*) The carrying device must be light in weight so that the inertia when moving the thermometer at considerable speeds is not excessive.

(*b*) The air through which the thermometer moves should be disturbed as little as possible by the reciprocation of the thermometer.

(*c*) Conditions favouring the formation of a pocket of air round the thermometer which could be carried with it must be avoided.

(*d*) The temperature throughout the path of the thermometer travel must be known, and means must be provided for independent measurement of this while the thermometer is reciprocating.

(*e*) The whole of the thermometer must be in a region of uniform temperature at any instant, and the compensating leads must be at the same temperature as the main leads at any corresponding part of their length.

### THE APPARATUS.

The apparatus comprises a silica tube, of which the upper part is heated by a resistance winding and the lower part is maintained cool by a water vessel. The resistance thermometer, stretched between the ends of a frame carried on slide bars and driven by a crank and connecting-rod mechanism, is reciprocated axially within the tube. A thermo-couple, used for determining the stationary temperature distribution within the tube, is stretched between the ends of another frame capable of movement by hand.

Leads from the thermometer are carried by swinging links to fixed terminals and thence to the Wheatstone bridge.

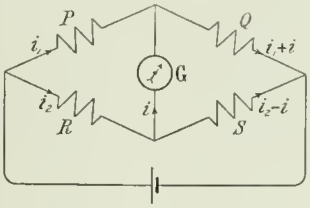


FIG. 1.

In making a set of tests, the stationary temperature distribution in the tube was explored by the thermocouple, previously calibrated, and the resistance thermometer, moved from point to point. The readings of the Einthoven galvanometer could then be translated direct into temperatures. The resistance thermometer was set reciprocating at a given speed and a plate was exposed in the galvanometer camera. This procedure was repeated for a range of speeds.

### THE MATHEMATICAL THEORY OF THE UNBALANCED WHEATSTONE BRIDGE.

In Fig. 1, let $P$, $Q$, $R$, $S$ be the resistances of the four arms of the bridge, and $G$ the resistance of the galvanometer. Let $e$ be the potential difference across the bridge and $v$ the potential difference across the galvanometer. Let $i_1$ be the current in P, $i_2$ the current in R and $i$ the current in the galvanometer.

Then the following results have been obtained :—

$$\begin{aligned} v &= iG \\ &= e\left(\frac{PSG-QRG}{RPG+QRG+PQR+PSG+QSG+PQS+PRS+QRS}\right) \quad (1) \end{aligned}$$

$$i = e\left(\frac{PS-QR}{RPG+QRG+PQR+PSG+QSG+PQS+PRS+QRS}\right) \quad (2)$$

### APPLICATION TO RESISTANCE THERMOMETER.

In the ordinary form of resistance thermometer, a resistance wire is inserted in the arm P of the bridge, and a pair of compensating leads is inserted in the arm Q to neutralize the effect of change in resistance of the main leads. In order that the compensation shall be accurate it is necessary that the resistance $S$ bear to $R$ the same ratio as the resistance of the compensating leads bears to the resistance of the main leads, and the balance obtained by adding extra resistance to the arm Q. It is convenient to make the compensating leads exactly similar to the main leads, and this necessitates $R$ and $S$ being equal. When a balance is obtained, therefore, $P = Q$. When a balance is not obtained, the difference of potential across the galvanometer is given, from Equation (1), by

$$\begin{aligned} v &= e\left[\frac{(P-Q)G}{(P+Q)\,(2G+R)+2PQ}\right] \\ &= e\left[\frac{P-Q}{(2+R/G)\,(P+Q)+(2PQ/G)}\right] \quad . \quad (3) \end{aligned}$$

This method of connecting up the Wheatstone bridge may be termed a " series " arrangement, since the thermometer and compensating circuits are in series with respect to the battery current. If we interchange the battery and galvanometer we obtain what may be termed a " parallel " arrangement, since the thermometer and compensating circuits will now be in parallel with respect to the battery current. This method of connecting up will now be considered. The most convenient way of doing this is to interchange $P$ and $S$ in Equation (1). This gives

$$v = e\frac{SPG-QRG}{SRG+QRG+SQR+SPG+QPG+SQP+SRP+QRP}$$

Putting $S = R$ we obtain :—

$$v = e\left[\frac{P-Q}{(1+R/G)\,(P+Q)+R+(2/G+1/R)PQ}\right] . \quad (4)$$

### THE RELATIVE ADVANTAGES OF " SERIES " AND " PARALLEL " ARRANGEMENTS.

In the resistance thermometer as generally used, for example in the Callendar temperature recorder, a slide wire is inserted between P and Q and a connection is made by means of a jockey at the balance point. Under these circumstances it is considered preferable that the sliding contact should not carry the main current, so the " series " arrangement is adopted, whereby the jockey only carries the galvanometer current, which is of necessity always small and which vanishes when a balance is obtained.

For measuring cyclically-varying temperatures, however, the slide wire is not necessary and other matters exert their claim for consideration, namely, the battery heating of the thermometer wire and the efficacy of the compensating circuit.

### BATTERY HEATING.

Prof. G. Forbes gives for bare overhead wires :—

$$\text{Current} = \sqrt{\left[\frac{d^3t}{320R}\right]}$$

where $d$ = diameter of wire in cm,

$t$ = difference in temperature between wire and air, in degrees C., and

$R$ = specific resistance of wire at limiting temperature, in ohms per cm cube.

According to this formula, if the specific resistance of platinum be assumed to be $44 \times 10^{-6}$ ohm per cm cube at 1 000° C., and the temperature difference be limited to 5 degrees C., the currents in the thermometer wire will be as follows :—

| Diam. of thermometer wire | Current |
|---|---|
| inch | amp. |
| 0·01 | 0·0764 |
| 0·00585 | 0·0342 |
| 0·0032 | 0·0138 |
| 0·0025 | 0·00958 |
| 0·002 | 0·00685 |
| 0·0015 | 0·00445 |
| 0·001 | 0·00242 |

In all the theoretical calculations these are assumed to be the maximum safe currents, and they form the basis of the comparison between the different arrangements and between different values of the resistances $R$ and $G$ in Equations (3) and (4).

If this current be constant, as it will be very nearly if the platinum resistance forms only a small part of the resistance of the whole circuit, the temperature difference when the platinum is at 0° C. (taking the specific resistance as $11 \times 10^{-6}$ ohm per cm cube) is found by the same formula to be 1·25 degrees C.

Thus, if this value be adopted, the heating of the platinum due to the battery current is quite negligible.

### COMPENSATION.

It will be noticed that in both Equations (3) and (4) the expressions $(P + Q)$ and $PQ$ occur in the denominator, consequently any increase in resistance which equally affects $P$ and $Q$ reduces the difference of potential across the galvanometer; in other words, the compensators do not compensate except when a balance is obtained. This is a serious matter when using the Wheatstone bridge for measuring cyclically-varying temperatures, and its effect has been considered.

The whole problem has been thoroughly worked out for the 0·0032 in. diameter measuring wire, and curves have been plotted from which the following deductions have been drawn :—

(1) If $R$ is greater than $P$, the parallel arrangement requires a higher E.M.F. than the series.

(2) If $R$ is greater than $P$, the parallel arrangement gives a greater sensitivity than the series.

(3) If $R$ is greater than $P$, the parallel arrangement gives better compensation than the series.

(4) With the series arrangement, greater sensitivity is obtained with a small value for $R$.

(5) With the parallel arrangement, greater sensitivity is obtained with a large value for $R$, but very little is gained by increasing $R$ beyond 150 ohms.

(6) With the series arrangement, better compensation is obtained with a large value for $R$, but the improvement is small.

(7) With the parallel arrangement, better compensation is obtained with a large value for $R$, but very little is gained by increasing $R$ beyond 150 ohms.

(8) For fibres which give the same deflection per millivolt, greater sensitivity and better compensation are obtained with a high-resistance fibre, but in neither case is there much to be gained by increasing $G$ beyond 200 ohms.

In view of these deductions, it was decided to adopt the parallel arrangement and fix the values of the constants $R$ and $e$ according to the following table, which also shows the calculated resultant value of $v$ corresponding to a temperature of 1 000° C., the bridge being balanced at 0° C.

| Diameter | $R$ | $e$ | $v$ for 1 000° C. |
|---|---|---|---|
| in. | ohms | volts | volt |
| 0·01 | 50 | 4 | 0·0058 |
| 0·00585 | 150 | 4 | 0·0060 |
| 0·0032 | 150 | 2 | 0·0094 |
| 0·0025 | 200 | 2 | 0·0097 |
| 0·002 | 300 | 2 | 0·0098 |
| 0·0015 | 400 | 2 | 0·0094 |
| 0·001 | 800 | 2 | 0·0076 |

The fibres supplied for use in the galvanometer had a resistance of the order of 20 ohms, and this value has been used in computing the above table.

In view of the fact that the compensation is not exact when the bridge is unbalanced, it is important that the carrying wires should change their resistance by as small an amount as possible. After some trials copper was selected as the most suitable material, for two reasons: first, because its specific resistance is so low that any change in resistance is small compared with the platinum resistance, and secondly, because its thermo E.M.F. with platinum is very small. The error due to heating of the copper wires is 0·85 per cent, against 5·7 per cent for stainless steel under the conditions adopted for the experiments.

### EXPERIMENTAL RESULTS.

The results of the experiments are shown in the following tables and Figs. 2 to 4. The quantity termed the " lag " is the difference between the thermometer temperature and the air temperature when the thermometer is in the region of maximum temperature.

During the course of the tests, the stationary temperature-distribution curve gradually changed. This is considered to be due to very slow drying of the lagging round the heating element, and accounts for the

### 0·01-INCH WIRE.

*Temperature Range 530 degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 160 | 30 | 0·057 | 1·5 |
| 161 | 87 | 0·164 | 4·3 |
| 162 | 95 | 0·179 | 5·5 |
| 163 | 108 | 0·204 | 7·2 |
| 164 | 145 | 0·274 | 13·5 |
| 165 | 180 | 0·340 | 20·6 |
| 166 | 178 | 0·335 | 26·2 |
| 167 | 210 | 0·396 | 32·6 |
| 168 | 250 | 0·470 | 47 |
| 169 | 230 | 0·435 | 78 |
| 170 | 255 | 0·480 | 146 |

### 0·00585-INCH WIRE.

*Temperature Range 495 degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 172 | 47 | 0·081 | 6·7 |
| 173 | 83 | 0·143 | 13·0 |
| 174 | 130 | 0·224 | 20·0 |
| 175 | 135 | 0·233 | 25·2 |
| 176 | 170 | 0·293 | 31·8 |
| 177 | 198 | 0·342 | 41·3 |
| 178 | 193 | 0·333 | 54·0 |
| 179 | 211 | 0·364 | 57·8 |
| 180 | 215 | 0·371 | 64·2 |
| 181 | 208 | 0·359 | 76·5 |
| 182 | 230 | 0·397 | 149 |
| 183 | 245 | 0·423 | 230 |
| 184 | 228 | 0·393 | 289 |

### 0·0032-INCH WIRE.

*Temperature Range 370 degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 68 | 55·1 | 0·15 | 6·3 |
| 69 | 51 | 0·14 | 13·3 |
| 70 | 78·5 | 0·21 | 21·6 |
| 71 | 92 | 0·25 | 33·1 |
| 72 | 139 | 0·38 | 44·1 |
| 73 | 176 | 0·48 | 51·0 |
| 74 | 185 | 0·50 | 57·0 |
| 75 | 197 | 0·53 | 65·6 |
| 76 | 205 | 0·56 | 76·5 |

### 0·0032-INCH WIRE.

*Temperature Range 260 degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 89 | 31 | 0·12 | 6·7 |
| 90 | 40 | 0·15 | 13·2 |
| 92 | 60 | 0·23 | 21·6 |
| 93 | 75 | 0·29 | 32·2 |
| 95 | 110 | 0·42 | 45·0 |
| 97 | 143 | 0·55 | 65·7 |
| 98 | 154 | 0·59 | 77·0 |

### 0·0032-INCH WIRE.

*Temperature Range 180 degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 79 | 2·5 | 0·01 | 6·3 |
| 80 | 6 | 0·03 | 13·4 |
| 81 | 30 | 0·17 | 21·0 |
| 82 | 40 | 0·22 | 34 |
| 83 | 60 | 0·33 | 44 |
| 84 | 77·5 | 0·43 | 52 |
| 85 | 77·5 | 0·43 | 57 |
| 86 | 85 | 0·47 | 64 |
| 87 | 100 | 0·56 | 76 |

### 0·002-INCH WIRE.

*Temperature Range 495 degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 119 | 15 | 0·03 | 13·4 |
| 120 | 10 | 0·02 | 20·5 |
| 123 | 32 | 0·06 | 45·6 |
| 124 | 28 | 0·06 | 56 |
| 125 | 40 | 0·08 | 77 |

### 0·0015-INCH WIRE.

*Temperature Range 314 degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 104 | 9·5 | 0·03 | 25·5 |
| 105 | 19 | 0·06 | 32·2 |
| 107 | 19 | 0·06 | 6·9 |
| 110 | 19 | 0·06 | 58·0 |
| 111 | 19 | 0·06 | 64·0 |
| 112 | 41 | 0·13 | 76·5 |
| 113 | 50·5 | 0·16 | 97·5 |
| 114 | 55 | 0·18 | 109·0 |

apparent inconsistency of the results obtained with different diameters of thermometer wire, which made it impossible to draw conclusions as to the way in which the lag depends on the diameter of the wire.

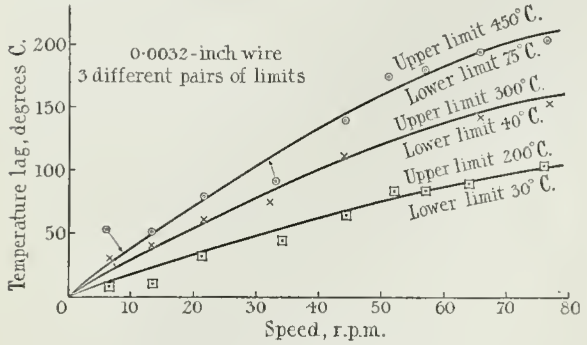


FIG. 2.

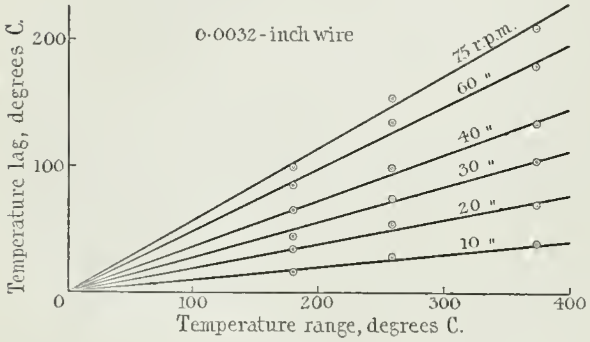


FIG. 3.

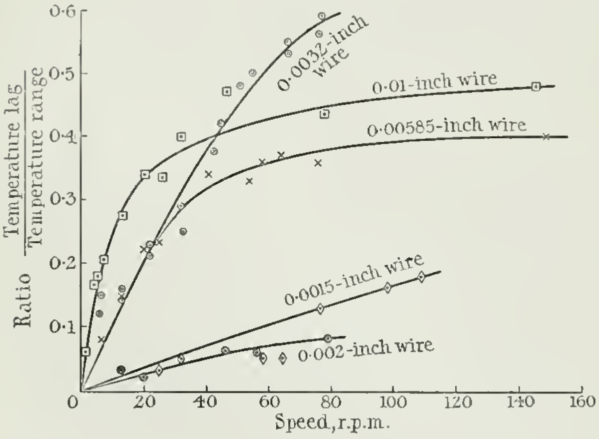


FIG. 4.

The results obtained with 0·001 in. diameter wire were not sufficiently concordant to be plotted, and the oscillations of the fine wire from its mean position appeared to be an important cause. A moving-thermometer type of apparatus is therefore not suitable for wire of this diameter.

However, sufficient work has been done to show that, at atmospheric pressure and with comparatively quiescent air, the platinum-resistance thermometer is not capable of following temperature-changes with sufficient accuracy for temperature measurement of the charge of a gas engine in operation.

It is anticipated that the conditions obtaining in the gas-engine cylinder are much more favourable to thermometry on account both of the higher pressures existing and also of the turbulence, and other experimenters are now working on a gas-engine type of apparatus to determine whether this is the case.

0·001-INCH WIRE.

*Temperature Range* 510 *degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 143 | 5 | 0·01 | 7·2 |
| 144 | 88 | 0·17 | 13·8 |
| 145 | 69 | 0·14 | 21·0 |
| 146 | 40 | 0·08 | 26·5 |
| 147 | 81 | 0·16 | 32·9 |
| 148 | 36 | 0·07 | 55·0 |

0·001-INCH WIRE.

*Temperature Range* 520 *degrees C.*

| Plate number | Lag | $\frac{\text{Lag}}{\text{Range}}$ | Speed |
|---|---|---|---|
| | deg. C. | | r.p.m. |
| 153 | 12 | 0·02 | 6·5 |
| 154 | 36 | 0·07 | 13·0 |
| 155 | 12 | 0·02 | 19·8 |
| 156 | 28 | 0·05 | 25·5 |
| 157 | 22 | 0·04 | 32·3 |
| 158 | 22 | 0·04 | 44·0 |

## CONCLUSION.

The whole of the casting, forging and machining, besides most of the pattern-making required in the construction of the apparatus, have been carried out in the Mechanical Engineering Department of the University of Birmingham, and a considerable amount of the authors' time was taken up with this work.

The thanks of the authors are due to the members of the staff of the workshops of the Department for assistance and facilities given in connection with the work.

# THE THEORY OF THE GENERATION OF ALTERNATING CURRENTS BY MEANS OF TRIODES.[*]

By N. SHUTTLEWORTH, M.Sc.

(*Paper first received 26th February, and in final form 11th May, 1923.*)

## SUMMARY AND INTRODUCTION.

The numerous circuits which have been suggested from time to time for the generation of alternating current by means of triodes are found by analysis to depend on the same basic principles.

The present paper is intended to cover the essential features of the subject, and is an endeavour to solve some of the difficulties on original lines and to offer an explanation of the characteristic behaviour of triodes in conjunction with generator circuits.

The problems connected with the generation of alternating current arise in particular in the production of high-frequency currents for wireless purposes, and, in order that the deductions may have practical utility, reference is often made in the context to the special requirements of wireless transmitting apparatus.

After a brief study of the characteristics of a triode or high-vacuum valve provided with three electrodes, viz. anode, grid and incandescent filament, the general circuit is considered and the factors determining the frequency of the generated current are established.

The particular limitations imposed by the triode and the conditions under which it is operated are then examined. It is shown that there is a definite maximum output to be obtained, and the requirements of the circuit for maximum output are investigated. The power obtainable under any given condition is determined. The design of a circuit to meet a specification is laid out and experimental confirmation is given. Finally a graphical method of analysis is evolved to show in diagrammatic form the conditions under which triodes may and do operate.

## TRIODE CHARACTERISTICS.

The curves of Fig. 1 are obtained from a particular but representative triode, and show the relations existing between the anode electron current and the potential of the grid, for numerous values of anode-to-filament voltage. It will be observed that the anode-current/grid-voltage relation is practically a straight line until saturation current is reached, and the effects of increments in anode voltage may be controlled by corresponding increments of grid voltage.

It will be shown later that the triode when operating under normal conditions is not influenced to any appreciable extent by the short, curved portion of the characteristic lines at very low anode current values, and it is permissible to replace the true characteristics by a series of parallel straight lines as shown in Fig. 2, the scale being the same as that used in Fig. 1. A line for zero anode voltage is introduced on the assumption that the characteristics remain unchanged down to zero voltage; it is not really necessary and is not strictly in accordance with facts.

The following deductions may then be made:—

A change of $A$ anode volts produces the same change in anode current as a change of $a$ grid volts.

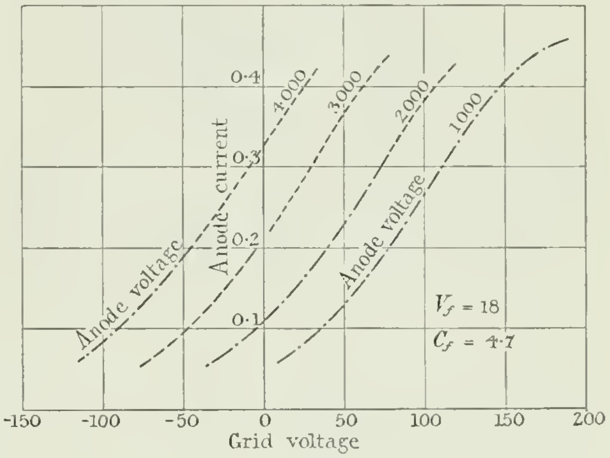


FIG. 1.

The ratio $A/a = m$ is termed the amplification factor of the triode.

Let $\mu$ = grid voltage.

Then anode current is given by:—

$$i_0 = \mu \tan\theta - d, \text{ for zero anode voltage.}$$
$$i_A = (\mu + a)\tan\theta - d, \text{ for anode voltage of } A.$$
$$i_{2A} = (\mu + 2a)\tan\theta - d, \text{ for anode voltage of } 2A.$$

In general the anode electron current is given by:—

$$i = \left(\mu + \frac{a}{A}V\right)\tan\theta - d, \text{ for anode voltage of } V \quad . \quad (1)$$

Again, $V/i$ may have any value according to the value of the voltage, $\mu$, on the grid, but $dV/di$ is a constant quantity for all values of $\mu$.

The ratio $dV/di$ may be termed the apparent resistance of the triode, and may be indicated by a constant, $r$. The value of $r$ is determined direct from the characteristics or from Equation (1) above by differentiation and substituting $\mu = 0$.

---

[*] The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

Differentiating with respect to $i$ we get :—

$$1 = \frac{a}{A} \times \frac{dV}{di} \tan \theta$$

that is
$$\frac{dV}{di} = r = \frac{m}{\tan \theta}$$

Whence we may write

$$i = \left(\mu + \frac{V}{m}\right)\frac{m}{r} - d$$

or
$$ri = m\mu + V - rd \quad . \quad . \quad . \quad . \quad (2)$$

This is a well-known equation in a particular form which expresses the relation between anode current ($i$), anode voltage ($V$), and grid voltage ($\mu$) for all values within working conditions. It is true for static conditions, and for oscillatory conditions if $i$, $V$ and $\mu$ be instantaneous values.

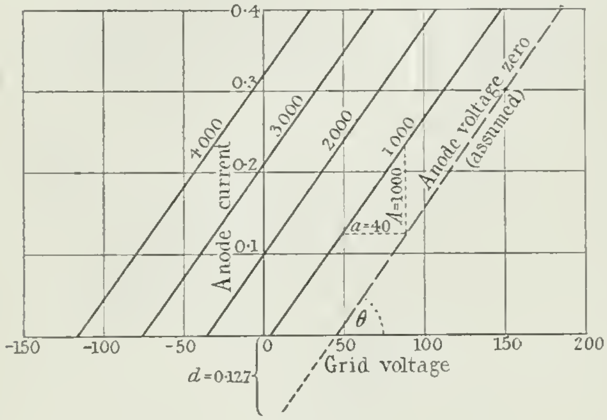


Fig. 2.

The following constants apply to the triode as determined from the curves :—

$A/a = m = 25.$

$r = m \tan \theta = 9\,000$ ohms.

$d = 0 \cdot 127$ ampere.

$rd =$ constant $= 1\,140.$

## Circuit for Generation of Alternating Current.

A suitable circuit for the production of alternating current is shown in Fig. 3. A direct-current generator, G, of voltage $E$ is the source of power supply, and across its terminals is placed a condenser of large capacity to by-pass any small alternating current which traverses it, without appreciable voltage-drop. In series with the generator is an inductance $L_K$ usually termed the anode choke, connected in turn to the anode of the triode, and to one side of a large condenser B termed the anode blocking condenser. The function of the latter is to prevent any direct current from passing through to the load circuit, and at the same time to act as the equivalent of a short-circuit to any alternating current passing through it ; in other words the alternating voltage-drop across it should be negligibly small.

The load circuit consists of an inductance L in parallel with a condenser C, and in one arm or the other a resistance R is shown through which the alternating current passes and energy is dissipated. If C were the capacity of a wireless transmitting aerial, R would be the equivalent aerial resistance.

The other extreme of the load circuit is connected to the filament of the triode and the negative terminal of the generator G.

Means for keeping the filament incandescent are not shown.

A coil of inductance $L_g$ connected between the grid and filament is inductively coupled to the inductance L in the load circuit, the mutual inductance between them being represented by $M$.

For efficient operation of the circuit it is necessary to introduce in the grid circuit a steady potential (shown in the figure as a battery S), but this may be more conveniently replaced by a high resistance with a condenser by-pass for alternating current.

A useful characteristic of the triode, not mentioned hitherto, is the production of a minute current through the grid circuit immediately the grid is held at a positive potential relative to the filament. This current is unidirectional and produces a d.c. voltage-drop across an inserted resistance which may be utilized, in place of the battery mentioned above, for providing a unidirectional voltage bias on the grid. Even unidirectional impulses of current are sufficient for the purpose, since they are practically smoothed out by the condenser placed in parallel with the grid resistance.

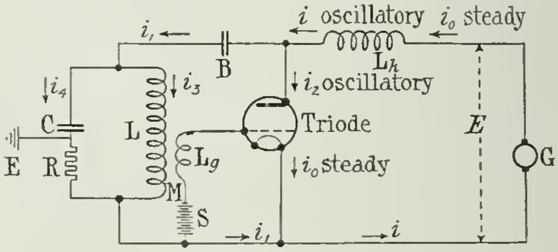


Fig. 3.

There are practical limitations in the circuit illustrated in Fig. 3, due to the fact that the alternating voltage across the inductance L or condenser C of the load circuit cannot exceed the pulsatory voltage allowable on the anodes of the triode or valve, and for this reason it is now the usual practice to tap off the anode connection at some fractional point or extension of the inductance included in the load or oscillatory circuit.

The more general case to be considered in detail is accordingly that shown in Fig. 4, where the inductance $L_1$ is that part of the total inductance in the oscillatory circuit included between the anode and filament of the triode, and $L_2$ is the remaining portion of the total inductance.

The steady or d.c. current from the generator $= i_0$, and it is assumed that superposed on this is an oscillatory current $i$. Since the steady current cannot pass through the anode blocking condenser, it must pass solely through the triode. The oscillatory current $i$ divides, a portion $i_1$ passing forward to the oscillatory or load circuit, and $i_2$ through the triode; thus the resultant current in the triode is $i_0$ on which is superposed $i_2$; the oscillatory current $i_1$ feeding the load circuit again divides, a portion $i_3$ passing through the inductance L₁ and $i_4$ through the inductance L₂, the condenser C and the load resistance R.

The steady voltage of the generator supply being $E$, let the oscillatory voltage superposed on $E$ at the anode of the triode $= V$. Further, let $\mu_0$ be the steady potential on the grid, and $\mu$ the oscillatory potential on the grid, then we have when oscillations as determined by Equation (2) are taking place :—

$$r(i_0 + i_2) = E + V + m(\mu + \mu_0) - rd$$

Similarly, when there is no oscillation or oscillatory current :—

$$ri_0 = E + m\mu_0 - rd$$

and, by subtraction

$$ri_2 = V + m\mu \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Again, the voltage on the anode is $(E + V)$, and the constant component $E$ is measurable across the anode blocking condenser, leaving a truly alternating voltage $V$ to be impressed on the load circuit. Neglecting the a.c. voltage-drop in the anode condenser, the pulsating voltage on the oscillatory or load circuit is the same in magnitude and of the same time phase as the pulsation between anode and filament of the triode. The following relations may now be expressed between the constants of the circuit :—

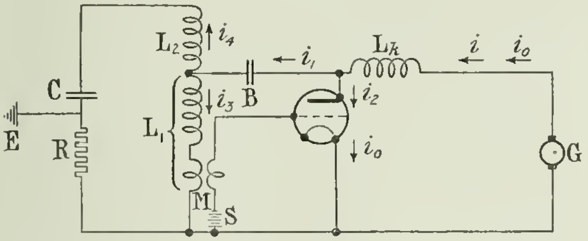


FIG. 4.

$$i = i_1 + i_2 = i_2 + i_3 + i_4$$

Voltage $\mu$ induced on the grid $= M\dfrac{di_3}{dt}$

Oscillatory voltage on anode of valve $= L_1\dfrac{di_3}{dt} = V$

and $$V = L_2\frac{di_4}{dt} + Ri_4 + \int\frac{i_4}{C}dt$$

Also, $$ri_2 = V + m\mu$$

or $$ri_2 = L_1\frac{di_3}{dt} + mM\frac{di_3}{dt} = \frac{di_3}{dt}(L_1 + mM)$$

Again, $$V = L_1\frac{di_3}{dt} = -L_K\frac{di}{dt}$$

$$i = i_1 + i_2 = i_2 + i_3 + i_4$$

$$\frac{di}{dt} = \frac{di_2}{dt} + \frac{di_3}{dt} + \frac{di_4}{dt}$$

or $$-\frac{L}{L_K}\times\frac{di_3}{dt} = \frac{L_1 + mM}{r}\frac{d^2i_3}{dt^2} + \frac{di_3}{dt} + \frac{di_4}{dt}$$

For $\dfrac{di_3}{dt}$ write $\dfrac{V}{L_1} = \dfrac{L_2}{L_1}\dfrac{di_4}{dt} + \dfrac{R}{L_1}i_4 + \dfrac{1}{L_1C}\displaystyle\int i_4dt$

and for $\dfrac{d^2i_3}{dt^2}$ write $\dfrac{L_2}{L_1}\dfrac{d^2i_4}{dt^2} + \dfrac{R}{L_1}\dfrac{di_4}{dt} + \dfrac{1}{L_1C}\times i_4$

then

$$\left[1 + \frac{L_1}{L_K}\right]\left[\frac{L_2}{L_1}\frac{di_4}{dt} + \frac{R}{L_1}i_4 + \frac{1}{L_1C}\int i_4dt\right] + \frac{di_4}{dt}$$
$$+ \frac{L_1 + mM}{r}\left[\frac{L_2}{L_1}\frac{d^2i_4}{dt^2} + \frac{R}{L_1}\frac{di_4}{dt} + \frac{1}{L_1C}i_4\right] = 0$$

Differentiating with respect to $t$, and arranging, we get :—

$$\frac{L_2}{L_1}\left[\frac{L_1 + mM}{r}\right]\frac{d^3i_4}{dt^3} + \left[1 + \frac{R}{L_1}\left(\frac{L_1 + mM}{r}\right)\right.$$
$$\left.+ \frac{L_2}{L_1}\left(1 + \frac{L_1}{L_K}\right)\right]\frac{d^2i_4}{dt^2} + \left[\frac{1}{L_1C}\left(\frac{L_1 + mM}{r}\right)\right.$$
$$\left.+ \frac{R}{L_1}\left(1 + \frac{L_1}{L_K}\right)\right]\frac{di_4}{dt} + \frac{1}{L_1C}\left(1 + \frac{L_1}{L_K}\right)i_4 = 0 \quad (4)$$

It may be assumed that the integral of this equation is of the form $i_4 = A \sin \omega t$, where $A$ is an exponential function which becomes unity when the conditions for the maintenance of oscillations are just satisfied, and has a positive index under stable conditions.

Hence, when continuous oscillations are established, it is possible to write :—

$$\frac{di_4}{dt} = \omega A \cos \omega t$$

$$\frac{d^2i_4}{dt^2} = -\omega^2 A \sin \omega t$$

$$\frac{d^3i_4}{dt^3} = -\omega^3 A \cos \omega t$$

By substituting these values in the equation a relation existing between the coefficients is obtained when the conditions for the maintenance of oscillations are fulfilled. Also, the foregoing being true for all values of $t$, we have when $t = 0$, $\sin \omega t = 0$ and $\cos \omega i = 1$.

Whence we have

$$-\frac{L_2}{L_1}\left[\frac{L_1 + mM}{r}\right]\omega^3A + \left[\frac{1}{L_1C}\left(\frac{L_1 + mM}{r}\right)\right.$$
$$\left.+ \frac{R}{L_1}\left(1 + \frac{L_1}{L_K}\right)\right]\omega A = 0$$

and when $\sin \omega t = 1$, $\cos \omega t = 0$, therefore

$$-\omega^2A\left[1 + \frac{R}{L_1}\left(\frac{L + mM}{r}\right) + \frac{L_2}{L_1}\left(1 + \frac{L_1}{L_K}\right)\right]$$
$$+ \frac{A}{L_1C}\left(1 + \frac{L_1}{L_K}\right) = 0$$

The first of these equations simplifies to

$$\omega^2 = \frac{\frac{1}{L_1C}\left(\frac{L_1 + mM}{r}\right) + \frac{R}{L_1}\left(1 + \frac{L_1}{L_K}\right)}{\frac{L_2}{L_1}\left(\frac{L_1 + mM}{r}\right)} \quad . \quad (5)$$

and the second simplifies to

$$\omega^2 = \frac{\frac{1}{L_1C}\left(1 + \frac{L_1}{L_K}\right)}{1 + \frac{R}{L_1}\left(\frac{L_1 + mM}{r}\right) + \frac{L_2}{L_1}\left(1 + \frac{L_1}{L_K}\right)} \quad . \quad (6)$$

It is evident from Equations (5) and (6) that there are two oscillatory frequencies possible with a circuit of this kind, but the one which concerns us most is that which may resonate with the constants of the load circuit, and this may be determined from Equation (6). By making $L_K$ large enough in comparison with $L_1$, the small fraction $L_1/L_K$ may become equal to $(R/L_1)[(L_1 + mM)/r]$ and may be substituted for it.

Equation (6) then becomes $\omega^2 = \dfrac{1/(L_1C)}{1 + (L_2/L_1)}$

or $$\omega^2 = \frac{1}{(L_1 + L_2)C}$$

and $$\omega = 2\pi \times \text{frequency} = \sqrt{\frac{1}{(L_1 + L_2)C}} \quad . \quad (7)$$

It will be observed that this frequency resonates with the circuit consisting of the condenser C and the total inductance across which it is connected; thus the generated frequency may be maintained at a constant value while the inductance $L_1$ across which the triode is placed may be varied.

The well-known result is obtained that $i_3$ and $i_4$ are almost equal and opposite, and in effect form a large circulating current within the closed circuit. The input current $i_1$ is a comparatively small energy current supplied at a high voltage across the load circuit; $Vi_1$ provides the losses $i_4^2R$ in the load resistance R; and $i_1$ is the vectorial sum of $i_3$ and $i_4$. The voltage $V$ across the load circuit is the pulsatory voltage across the anode and filament of the triode, and consideration indicates that this cannot have a peak value $E_1$ which exceeds the steady voltage $E$ of the supply.

Since there is an upper limit to the voltage pulsation on the triode, this only applies to the voltage on the inductance $L_1$, so the total voltage on $(L_1 + L_2)$ may be regulated by simply changing the proportion of $L_1$ to $L_2$. Provided the highest possible voltage pulsation on the anode of the triode can be maintained, the voltage, and therefore the current in the load circuit, can be increased to any value desired. It will be seen presently, however, that there are other limitations.

The generated frequency as determined from Equation (6) must still hold true for Equation (5), and by substitution the requisite value of $M$ which will fulfil this condition is obtained. By substituting $1/(L_1 + L_2)C$ for $\omega^2$ in Equation (5) we get:—

$$\frac{1}{(L_1 + L_2)C} \times \frac{L_2}{L_1}\left(\frac{L_1 + mM}{r}\right)$$
$$= \frac{1}{L_1C}\left(\frac{L_1 + mM}{r}\right) + \frac{R}{L_1}\left(1 + \frac{L_1}{L_K}\right)$$

which reduces to

$$-M = \frac{L_1}{m} + \frac{(L_1 + L_2)RCr}{L_1m}\left(1 + \frac{L_1}{L_K}\right) \quad . \quad (8)$$

This expression determines the minimum coupling between grid and load circuit at which persisting alternating current can be generated.

CONTROL OF THE STEADY POTENTIAL OF THE GRID.

We have already seen that for static conditions of the triode:—

$$ri_0 = E + m\mu_0 - rd \quad . \quad . \quad . \quad . \quad (9)$$

where $i_0$ is the steady current from the source of supply. When oscillating we have:—

$$ri_2 = V + m\mu \quad . \quad . \quad . \quad . \quad (3)$$

or $$rI_2 = E_1 + m\mu_{max.}$$

where $I_2$ is the peak value of the oscillatory portion of the current through the triode; $\mu_{max.}$ is the peak value of the oscillatory grid voltage, and $E_1$ is the maximum value of $V$.

It is important to note that in the first of these equations, $r$, $E$, $m$ and $d$ are fixed, and that the steady current $i_0$ flowing in the circuit is controlled by the steady potential $\mu_0$ of the grid. When the triode is oscillating these conditions are in no way affected, but while the steady potential $\mu_0$ controls the steady current $i_0$ so also under working conditions, when $V$ is approximately constant, the oscillatory potential $\mu$ of the grid controls the oscillatory portion of the current $i_2$ through the triode. The resultant current through the triode is $i_2$ superposed on $i_0$, and it will be apparent later that the minimum value occurs when there is maximum potential on the anode; hence, in order to avoid excessive losses in the triode, it is essential that the resultant current be reduced to zero at one moment of the cycle, since, if this were not done, steady current would be flowing uselessly through it. It is therefore necessary to know the grid potential which can stop current from flowing through the triode.

Current will be cut off through the triode if $I_2$ be greater than or equal to $i_0$, viz. if $rI_2 =$ or $> ri_0$

or $$E_1 + m\mu_{max.} = > E + m\mu_0 - rd$$
$$m\mu_{max.} - m\mu_0 = > E - E_1 - rd$$

or $$\mu_{max.} - \mu_0 = > \frac{E - E_1 - rd}{m} \quad . \quad . \quad (10)$$

From the characteristics given in Fig. 2, $rd = 1\,140$, while $E$ may be any voltage up to, say, 8 000 volts. $E_1$ will approach $E$ in value so long as the emission current from the filament can meet the requirements of the circuit, i.e. so long as the triode is not overloaded. Thus under normal conditions the value of $(E - E_1 - rd)/m$ is always negative, and, to ensure that current is entirely cut off through the triode for a portion of the cycle, it is only necessary that $\mu_{max.}$ be greater than $\mu_0$.

However, the maintenance of a steady grid potential by means of a grid current flowing through a grid-leak resistance is based on the fact that $\mu_{max.}$ must be greater than $\mu_0$, because it is $(\mu_{max.} - \mu_0)$ which determines the flow of grid currents, viz. the fact that the grid does for a short period become positive relatively to the filament when $\mu_0$ is a constant negative voltage.

With grid-leak resistance control of the steady grid potential it is evidently not possible to depart seriously from efficient operation of the triode. This is true until the grid current fails, and this can only happen when $E_1$ falls far short of $E$, due to insufficient emission current from the filament to meet the demands imposed.

These deductions are confirmed by experimental observation; if the grid current is falling and $E_1$ is becoming seriously reduced relatively to $E$, it is possible to restore both by increasing the temperature of the filament.

### FURTHER DEDUCTIONS FROM THE GENERATOR CIRCUIT.

It is important to note that the value of the mutual inductance $M$ as derived in Equation (8) passes through a minimum value as the inductance $L_1$ is varied from a high to a low value. Now $M$ is a measure of the pulsatory voltage on the grid, $L_1(di_3/dt)$ is the anode voltage pulsation and $M(di_3/dt)$ is the grid voltage pulsation, or $M/L_1$ is the ratio of the grid to anode pulsations. Therefore, when $M$ is more than a fraction of $L_1$ it means that the grid voltage is higher than the anode voltage, which is manifestly not practical. There is in fact no practical utility in decreasing the anode inductance $L_1$ below the point which gives a minimum value for $M$. The object of decreasing $L_1$ is to obtain more current and more power in the load circuit, but it is also necessary with this object to keep minimum pulsatory voltage on the grid. It has been shown in the preceding section that the pulsatory voltage $\mu$ on the grid determines the magnitude of the steady potential $\mu_0$ on the grid, and the latter in turn controls the magnitude of the direct current which can be drawn from the source of supply. It is only with minimum negative steady potential on the grid that maximum direct current can be obtained from the supply, therefore maximum input (and with it output in the load circuit) can only be obtained with minimum oscillatory potential on the grid; in other words, when $M$ is a minimum with regard to $L_1$.

To determine the minimum value of $M$ differentiate Equation (8) with respect to $L_1$ and equate to zero.

Then $$0 = -\frac{1}{m} + \frac{(L_1 + L_2)RCr}{L_1^2 m}\ *$$

or $$L_1^2 = (L_1 + L_2)RCr$$

but $$(L_1 + L_2)C = 1/\omega^2$$

therefore $$L_1 = \sqrt{(Rr)}/\omega \quad . \quad . \quad . \quad . \quad (11)$$

This expression gives the inductance below the anode tapping point, according to the frequency to be generated, which will draw maximum current from the source of supply and give the highest obtainable current in the load circuit. It is assumed, of course, that the voltage, $E$, of the supply, remains constant; if this is increased then all currents and all voltages throughout the circuit increase in like proportion, and the power output is increased accordingly, but the importance of the above is apparent when $E$ is already as high as can safely be allowed. To reduce $L_1$ below the value calculated, results in a reduction of the possible voltage pulsation on the anode of the triode and consequently a fall in the efficiency of operation.

The amount of power which can be put into the load circuit under the above conditions will receive consideration in the next section, but it will be apparent here that having once fixed the dimensions of the electrodes of a triode and determined $r$ and the safe working voltage $E$, there is a limit to the power for which it can be usefully employed. There is also a corresponding limit to the power which will be dissipated internally under efficient conditions, and from this the upper limits to the dimensions of the envelope can be fixed.

There are, however, other limitations which may be imposed by the triode. There is, for instance, a limit to the amount of heat capable of being dissipated from the metal of the anode, and if this be smaller than the power dissipation which should take place within the triode when working up to the limits imposed by the internal resistance $r$, the usefulness of the triode is reduced and the size of the envelope may be correspondingly reduced.

The amount of power which an anode can dissipate continuously without attaining too high a temperature may be found under static conditions and now forms a standard test to be imposed before acceptance of triodes.

Further, there is a saturation current or maximum emission current with a fixed filament temperature which cannot be exceeded and represents the instantaneous peak value of the current which can pass through the triode. It will be shown later that there is a relation between the triode current and the true energy current passing into the load circuit; hence again this may prove to be a limiting factor to the possible power obtainable in the load circuit.

These limitations appear according to the conditions under which the triode is operated, and will receive attention again when expressions for power input have been deduced.

### POWER IN THE LOAD OR AERIAL CIRCUIT.

To determine the actual power which will pass into the load or oscillatory circuit it is necessary to know :—

(a) The effective impedance and admittance of the load circuit between the anode tapping point and filament into which the current $i_1$ is fed.

(b) The power factor of the same circuit.

The power and current can then be determined from the pulsation of the anode voltage $V$, of which $E_1$ is the peak value; $V$ therefore equals $E_1/\sqrt{2}$.

---

* $L_1 + L_2$ is constant.

Let $g$ = resultant conductance,
$b$ = resultant susceptance.

Then $\sqrt{(g^2 + b^2)}$ = admittance

and $i_1 = V\sqrt{(g^2 + b^2)}$

The power factor of the circuit $= \dfrac{g}{\sqrt{(g^2 + b^2)}}$

The power input to the circuit $= V \times i_1 \times$ power factor
$= V^2 \times g$

The reactance of the single circuit containing $L_2$, $C$ and $R$ is:—

$$\omega L_2 - \frac{1}{\omega C}$$

Resistance $= R$

$$\text{Conductance } g_1 = \frac{R}{R^2 + \left(\omega L_2 - \dfrac{1}{\omega C}\right)^2}$$

The conductance of the circuit containing $L_1$ is zero, hence the resultant conductance of the two circuits in parallel is:—

$$g = \frac{R}{R^2 + \left(\omega L_2 - \dfrac{1}{\omega C}\right)^2}$$

The susceptance of the first circuit is:—

$$\frac{\omega L_2 - \dfrac{1}{\omega C}}{R^2 + \left(\omega L_2 - \dfrac{1}{\omega C}\right)^2}$$

The susceptance of the circuit containing $L_1$ is $\dfrac{1}{\omega L_1}$, hence the susceptance of both in parallel is:—

$$b = \frac{1}{\omega L_1} + \frac{\omega L_2 - \dfrac{1}{\omega C}}{R^2 + \left(\omega L_2 - \dfrac{1}{\omega C}\right)^2}$$

Inserting the condition that $\omega^2 = \dfrac{1}{(L_1 + L_2)C}$ we obtain

$$g = \frac{R}{R^2 + \omega^2 L_1^2}\,^*$$

and $$b = \frac{R^2}{\omega L_1(R^2 + \omega^2 L_1^2)}$$

hence $$g^2 + b^2 = \frac{R^2}{\omega^2 L_1^2(R^2 + \omega^2 L_1^2)}$$

The power factor of the circuit is:—

$$\frac{g}{\sqrt{(g^2 + b^2)}} = \frac{\omega L_1}{\sqrt{(R^2 + \omega^2 L_1^2)}}$$

and this is practically unity, since $R$ is usually small compared with $\omega L_1$.

It is now possible to write:—

Power input to load circuit

$$= V^2 g = \frac{E_1^2}{2} \times \frac{R}{R^2 + \omega^2 L_1^2} \quad . \quad . \quad (12)$$

The maximum possible power input is obtained when

$$L_1 = \sqrt{(Rr)}/\omega \quad \text{[see Eqn. (11)]}$$

*Hence the maximum power obtainable in an oscillatory or load circuit* becomes

$$\frac{E_1^2}{2} \times \frac{R}{R^2 + Rr} = \frac{E_1^2}{2} \times \frac{1}{R + r} \text{ watts} \quad . \quad (13)$$

Since $R$ is usually small compared with $r$, and $E_1$ approaches $E$, this expression becomes practically $E^2/2r$ watts.

This deduction establishes two important conclusions:

(1) The power obtainable in the load circuit by the use of a given triode is entirely independent of its amplification factor, $m$, or in other words the design of the grid within reasonable limits has no material influence. (It must be borne in mind that the grid must have sufficient influence to produce practically straight-line characteristics for the triode as included in the original hypothesis.)

(2) There is a definite limit to the power obtainable from a given triode operated at a fixed voltage. This limit is determined by the apparent internal resistance, which in turn depends principally on the distance between anode and filament and the possible emission current from the filament. Thus, assuming a given length of filament raised to the highest working temperature, the resistance $r$ is reduced by diminishing the clearance between anode and filament, and the extent to which this reduction can be carried depends on the voltage at which the triode is to operate. Maximum voltage occurs between grid and anode, and the space occupied by a suitable grid must be allowed for.

Further, if triodes are operated in parallel the effective value of $r$ is inversely proportional to the number in use, so that the possible power output can be increased to any extent desired by simply increasing the number of triodes.

It is now possible to establish the relation between the various currents in the circuit, both as regards magnitude and phase difference.

The energy current $i_1$ passing into the load or oscillatory circuit is given by

$$V\sqrt{(g^2 + b^2)} = \frac{E_1}{\sqrt{2}} \times \frac{R}{\omega L_1\sqrt{(R^2 + \omega^2 L_1^2)}}$$
$$= \frac{ER}{\sqrt{2}\,\omega^2 L_1^2} \text{ (practically)} \quad . \quad (14)$$

Also $i_3$, the current in the load-circuit inductance, is

$$\frac{V}{\omega L_1} = \frac{E}{\sqrt{2}\,\omega L_1} \text{ (practically)}$$

$i_3$ is 90° in time phase behind the voltage $V$, and therefore practically 90° behind $i_1$.

---

* Note that $\omega L_2 - 1/(\omega C) = -\omega L_1$.

$i_4$ is (numerically) almost equal to $i_3$ and differs by nearly 180° in time phase.

$$\text{The ratio } \frac{i_1}{i_3} = \frac{\text{aerial energy current}}{\text{aerial current}}$$

$$= \frac{R}{\sqrt{(R^2 + \omega^2 L_1^2)}} = \frac{R}{\omega L_1} \text{ (practically)}$$

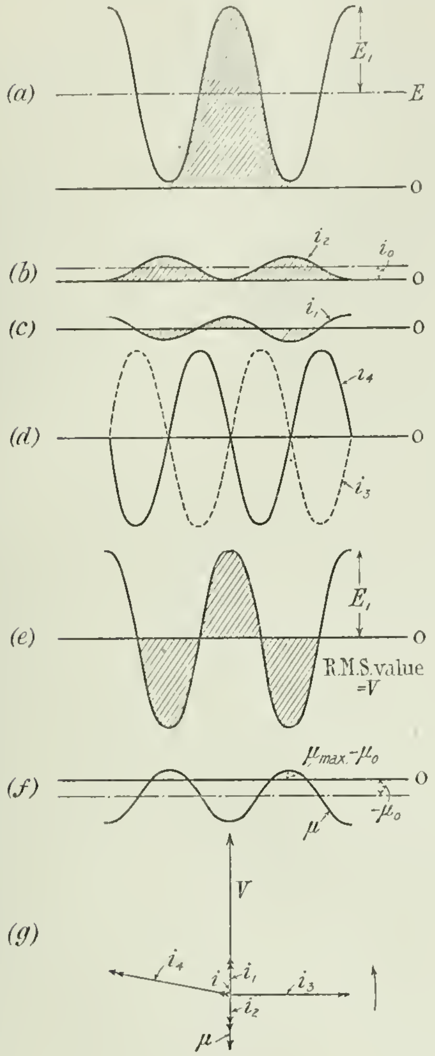


FIG. 5.

(a) Anode voltage variation.
(b) Current in triode.
(c) Energy current in oscillatory circuit.
(d) Current circulating in oscillatory circuit.
(e) Alternating voltage below anode tapping.
(f) Grid voltage pulsation.
(g) Vector diagram.

In normal wireless transmitting circuits $\omega L_1$ is 10 to 100 times the resistance $R$.

The current $i_1$ is a small energy current added vectorially to the wattless current $i_3$ to make up the aerial current $i_4$.

Again, it has been shown that :—

$$i^2 = -\frac{RC(L_1 + L_2)}{L_1}\left(1 + \frac{L_1}{L_K}\right)\frac{di_3}{dt}$$

and $C(L_1 + L_2) = 1/\omega^2$, while $L_1/L_K$ is negligibly small, and $\frac{di_3}{dt} = \omega i_3$, since $i_3$ is sinusoidal.

$$\text{Whence} \qquad i_2 = -\frac{R}{\omega L_1} i_3$$

But $i_1$ is shown above to be practically $(R/\omega L_1)i_3$, therefore if $i_1$ be considered in a positive sense, the direction of $i_2$ is instantaneously opposite to that shown by the positive arrow in Fig. 4, and $i_1$ with $i_2$ may be looked upon as one and the same current circulating between the triode and load circuit. The minute difference between $i_1$ and $i_2$ is made up by the negligibly small current $i$ flowing through the anode choke inductance $L_K$.

The voltages and currents in the circuit are represented in Fig. 5.

It should be noted that at the moment of highest potential on the anode relative to the filament of the triode, the grid potential is so highly negative as to cut off all current through it, while the maximum current through the triode occurs at the moment of minimum anode potential in relation to the filament. It is clear, therefore, that the triode must be designed to give its full emission current at a very low voltage on the anode, such voltage being a fraction only of the supply voltage $E$, otherwise the magnitude of the pulsatory voltage with peak value $E_1$ would be too small a proportion of $E$ to give a satisfactory operating efficiency.

Let it be assumed now that a suitable emission current is obtained in the triode and that $E_1$ may be kept within a few per cent of $E$ (this is quite possible in practice), so that $E = E_1$ (virtually).

The direct input to the circuit $= Ei_0$ watts and $i_0 = \sqrt{2} i_2$ if the triode current is momentarily cut off at one instant [Fig. 5 (*b*)].

$$\text{Also } i_2 = i_1 = \frac{ER}{\sqrt{2}\omega^2 L_1^2} \text{ (practically) [see Eqn. (14)]}$$

Hence the d.c. power input is

$$= E \times \sqrt{2} \times \frac{ER}{\sqrt{2}\omega^2 L_1^2} = \frac{E^2 R}{\omega^2 L_1^2}$$

The corresponding input to the load circuit

$$= \frac{E^2}{2} \times \frac{R}{\omega^2 L_1^2} \text{ [see Eqn. (12)]}$$

Hence the efficiency of the circuit $= \frac{1}{2} = 50$ per cent.

This value for the efficiency assumes that $E_1 = E$ and that the currents $i_1$ and $i_2$ are sinusoidal. It will be shown later, however, that when $i_1$ and $i_2$ are forcibly made to depart from sinusoidal shape, a very much higher operating efficiency than 50 per cent may be obtained.

### DESIGN OF CIRCUIT.

For the present let it be assumed that the operating efficiency is $\epsilon$ (it must necessarily vary according to the size of apparatus and circuit to be designed and the degree of economy in expenditure).

Let the amount of heat which can be continuously dissipated from the anode of a triode be represented by $W$ watts. If the triode is to be used for wireless signalling it is only operating during the signals, which do not occupy more than half the total time, and the rating in watts may be correspondingly increased ; this is taken into account in assigning a value to $W$.

With $n$ triodes in use the total dissipation allowable is $nW$ watts, and the input to the oscillatory circuit is represented by $\epsilon/(1-\epsilon)\times nW$ watts.

The maximum possible power output to an oscillatory circuit by the use of $n$ triodes is

$$= E_1^2 n/2r \text{ [see Eqn. (13)]}$$

hence it is essential that $E_1^2 n/2r$ be greater than $\epsilon/(1-\epsilon)\times nW$ or that $E_1^2/2r$ be greater than $\epsilon/(1-\epsilon)\times W$.

This means that with a given number of triodes there is a minimum voltage of the supply at which the desired power can be obtained in the oscillatory circuit, and $E$ should be reasonably higher than this minimum.

A suitable value of $E$ may be determined from the above ; it is then known beforehand that the tapping point for the anodes on the aerial or load circuit inductance will not need to be reduced to that point at which the highest possible output is obtained.

The power given to the oscillatory circuit is also

$$\frac{E_1^2}{2}\times\frac{R}{R^2+\omega^2L_1^2} \text{ [see Eqn. (12)] or practically } \frac{E_1^2R}{2\omega^2L_1^2}$$

$$\text{hence } \frac{E_1^2R}{2\omega^2L_1^2}=\frac{\epsilon}{1-\epsilon}nW = \text{aerial power in watts.}$$

Or

$$L_1=\frac{E}{\omega}\sqrt{\left(\frac{R}{2\times\text{aerial watts}}\right)} \text{ in henrys (nearly)} \quad . \quad (15)$$

If the filament emission current is such that $E_1$ cannot approach $E$ it is necessary to substitute $E_1$ in the above.

Instead of expressing the generated current in terms of frequency as involved in $\omega$, it may be expressed in terms of wave-length in metres,

$$\text{or} \qquad \omega=\frac{6\pi\times10^8}{\text{wave-length (metres)}}$$

and

$$L_1=\frac{E_1\times\text{wave-length}}{600\pi}\sqrt{\left(\frac{R}{2\times\text{aerial watts}}\right)} \text{ in microhenrys}$$

or

$$L_1=\frac{E_1\times\text{wave-length}}{2\ 665}\sqrt{\frac{R}{\text{aerial watts}}} \text{ in microhenrys}$$

This expression determines that part of the inductance in the oscillatory circuit included below the tapping point of the anodes of the triodes.

It has already been shown that

$$\omega = 1/\sqrt{\{(L_1+L_2)C\}}$$

therefore wave-length $= 6\pi\times10^8\sqrt{\{(L_1+L_2)C\}}$

where $(L_1+L_2)$ is inductance in henrys, and $C$ is the aerial or oscillatory circuit condenser capacity in farads. If $C$ be fixed, then $(L_1+L_2)$ may be determined for any wave-length or generated frequency.

The current in the oscillatory circuit is determined by $R$, since $(\text{current})^2\times R=$ aerial watts.

Thus the proportions of a suitable circuit are complete.

## GENERAL CONSIDERATIONS.

The accuracy of the foregoing deductions may be readily confirmed by experiment on apparatus sufficiently large to enable reliable measurements to be made.

The test-results given in the table are obtained from two triodes with the characteristics shown in Fig. 1, operated in parallel. The oscillatory circuit is tuned to a wave-length of 1 000 m (i.e. $3\times10^5$ periods per sec.) and the effective resistance of the oscillatory circuit is 3·2 ohms. Each triode can dissipate 400 watts internally before the metal of the anode becomes unduly hot, and this is considered to be the full rating.

A working efficiency of 60 per cent is to be expected at full rating, so with two triodes dissipating 800 watts it should be possible to obtain 1 200 watts in the oscillatory circuit.

The maximum possible power output to the oscillatory circuit $=E_1^2/(2r)$, where $r$ for two triodes $=\frac{1}{2}$ (9 000) $=$ 4 500 ohms. If then $E_1^2/(2\times4\ 500)=1\ 200$, or $E_1 = 3\ 290$ volts, it will just be possible to obtain 1 200 watts in the oscillatory circuit.

The corresponding value of $E$ is somewhat higher than $E_1$, the ratio $E_1/E$ depending on the amount of current that will be required to pass through each triode, as compared with the saturation value of the emission current from the hot filament. Naturally, if a triode is fully loaded in one respect it should be near its full rating in other respects, and this will be the case under the conditions in question, the current in each triode reaching its saturation value even before the full output is reached. In consequence $E_1$ is likely to fall seriously between no-load and full-load conditions while $E$ is kept constant, but $(E-E_1)$ must not be more than 1 140 $= rd$ or there would be liability of the grid-leak current failing and inefficient operation resulting, as shown in a previous section. If the triode has not sufficient emission current it may not be able to prevent $(E-E_1)$ exceeding the limit of 1 140 volts. It is therefore concluded that a value of $E=4\ 500$ volts approaches the lowest value it is safe to use if an output of 1 200 watts is required in the oscillatory circuit.

This value of $E$ may be termed the critical voltage of the triode ; it is the lowest voltage at which it is possible effectively to load the triode to its full rating, and retain efficient working.

At higher supply voltages than the critical value a higher power output to the oscillatory circuit can be obtained, but this cannot be endured continuously by the triodes on account of excessive internal loss. It will therefore be found necessary to keep the inductance $L_1$ (included below the anode tapping point) at a higher value than that at which maximum power to the

Test-Results obtained with Two Triodes having Characteristics as shown in Fig. 1.

| Column .. .. .. .. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D.C. supply voltage, $E$.. .. | 4 500 | 4 500 | 4 500 | 4 500 | 4 500 | 4 500 | 4 500 | 7 000 | 7 000 | 7 000 | 2 500 | 2 500 | 2 500 | 2 500 | 2 500 | 2 500 | 2 500 | 2 500 |
| Inductance $L_1$, in microhenrys below anode tapping point | 108 | 100 | 91 | 83 | 73 | 63 | 53 | 125 | 117 | 108 | 108 | 100 | 91 | 83 | 73 | 63 | 53 | 43 |
| Voltage on inductance $L_1$ (R.M.S. value $= V$) | 2 750 | 2 640 | 2 580 | 2 550 | 2 350 | 2 180 | 1 200 (approx.) | 4 430 | 4 230 | 4 170 | Not measured. | | | | | | | |
| $E_1 = \sqrt{2}V$ .. .. .. | 3 890 | 3 730 | 3 650 | 3 600 | 3 320 | 3 080 | — | 6 250 | 5 980 | 5 880 | | | | | | | | |
| $E_1/E$, per cent .. .. .. | 86·4 | 82·8 | 81 | 80 | 73·8 | 68·5 | — | 89·3 | 85·5 | 84 | | | | | | | | |
| D.C. input (amps.) .. .. | 0·16 | 0·175 | 0·205 | 0·245 | 0·31 | 0·385 | 0·25 | 0·198 | 0·215 | 0·245 | 0·09 | 0·13 | 0·135 | 0·15 | 0·20 | 0·26 | 0·30 | 0·37 |
| D.C. input (watts) .. .. | 720 | 788 | 922 | 1 100 | 1 395 | 1 730 | 1 125 | 1 385 | 1 505 | 1 715 | 225 | 325 | 337 | 375 | 500 | 650 | 750 | 925 |
| Current in oscillatory or aerial circuit, viz. in $L_1$. in amps. | 13·5 | 14·2 | 15·1 | 16·0 | 17·0 | 18·5 | 12·5 | 18·8 | 19·2 | 20·5 | 7·5 | 8·6 | 9·0 | 9·5 | 10·5 | 11·5 | 12·6 | 11·3 |
| Watts in aerial circuit = amps.$^2$ $\times 3\cdot2$ ohms | 582 | 645 | 730 | 820 | 925 | 1 095 | 500 | 1 130 | 1 180 | 1 342 | 180 | 237 | 259 | 288 | 353 | 424 | 508 | 407 |
| Percentage efficiency, neglecting filament heating | 80·8 | 81·8 | 79·2 | 74·5 | 66·4 | 63·5 | 44·5* | 81·5 | 78·5 | 78·4 | 80 | 73 | 77 | 77 | 70·5 | 65·3 | 67·6 | 44* |

* Readings could only be obtained by increasing the filament temperature.

oscillatory circuit is obtained, in order to restrain the demand for power.

At lower voltages than the critical value the power outputs to the oscillatory circuit are correspondingly reduced, and when operating at maximum output the internal loss of the triode is well within the rating and the anode does not heat up.

If, however, the anode tapping inductance $L_1$ is reduced below that for maximum output, or, alternatively, if the oscillatory circuit resistance is increased, thus necessitating a higher inductance $L_1$ for the point of maximum output, the operation will be very inefficient and the metal of the anodes may heat up.

These test-results show that with an operating voltage of 4 500 for the supply an output of 1 200 watts to the oscillatory circuit would, as expected, be obtained if the inductance $L_1$ below the anode tapping point were approximately 60 $\mu$H, and for an inductance only slightly less than this the circuit ceases to operate in a really stable manner, showing that maximum output has been reached.

According to calculation from theory, maximum output is obtained when

$$L_1 = \sqrt{(Rr)}/\omega \text{ henrys} = \sqrt{(Rr)}/\omega \times 10^6$$
$$= \sqrt{(3\cdot2 \times 4\,500)}/(2\pi \times 3 \times 10^5) \times 10^6 = 63\,\mu\text{H}$$

The agreement is sufficiently close to confirm the validity and usefulness of the original hypothesis.

Variations in aerial power with changes in the inductance $L_1$, or in the supply voltage, are clearly shown.

### Derivation of other Generator Circuits.

Referring again to the circuit of Fig. 4, it has been shown that the ratio of the inductances $L_1$ and $L_K$ should be very small. In a particular case let the inductance of the anode choke $L_K$ be infinite, as is clearly permissible from the theory, then, so far as the passage of alternating current through it is concerned, the circuit of $L_K$ may be broken. It was also shown that the d.c. supply voltage was absorbed and was measurable across the anode blocking condenser B; let the generator then be connected across B. The resulting circuit is shown in Fig. 6, and will be recognized as the well-known Lieben circuit.

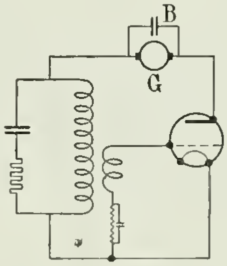


Fig. 6.

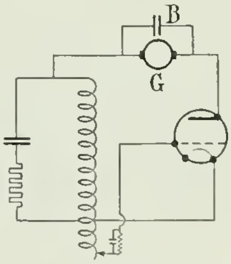


Fig. 7.

Other modifications may be obtained, according to the method of deriving the oscillatory grid voltage. It has been proved to be necessary for M to have a negative coupling, or for the grid-to-filament voltage to be opposite in phase to the anode-filament voltage. This suggests the circuits of Figs. 7 and 8. Again, a condenser and inductance in series may be shunted across $L_1$ or $L_1$ and $L_2$ or any part thereof, as in Fig. 9, the condenser being so small as not to affect the tuning of the oscillatory circuit to any appreciable extent. Due to the condenser being so small, it has a voltage across it greater than that across the inductance $L_1$ itself, hence the voltage across the series inductance is opposite to that across $L_1$, and if suitably proportioned it may be connected directly to the grid of the triode.

This method is, perhaps erroneously, termed "capacity coupling." Capacity coupling is recognized as being a connection through a condenser of negligible impedance, such condenser of itself forming no effective part of the circuit beyond acting as a short-circuit for alternating current and a block for direct current. When a condenser is effective for some purpose, it must form either a simple series or parallel connection and the term "coupling" is redundant. Alternatively to Fig. 9 the capacity between anode and grid of the triode may be utilized, a simple inductance being connected between grid and filament. On moderately large triodes highly efficient operation may be obtained in this way without the necessity for electromagnetic coupling to the grid inductance.

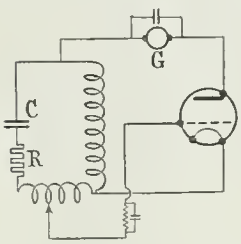


FIG. 8.

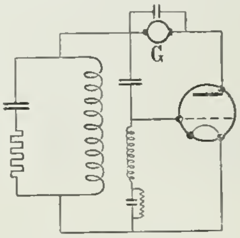


FIG. 9.

It has been assumed hitherto that the actual capacities between the electrodes of the triode are negligible compared with the capacity dealt with in the oscillatory circuit. In practical wireless circuits this assumption is legitimate, but at the same time in large installations the capacity current flowing is measurable and may be utilized as indicated above.

### OSCILLATION LINES.

It will now be shown how the expressions obtained for the coupling of grid to aerial, aerial power, steady grid potential, triode current, etc., may be embodied in a diagram in such a way as to indicate the effect of any change and show the conditions imposed upon the triode.

This can be done by the aid of the original diagram showing the anode-current/grid-voltage relation at different anode voltages.

It is necessary first to establish the relationship between grid and anode pulsatory voltages.

$$\frac{\text{A.C. voltage on grid}}{\text{A.C. voltage on anode}} = \frac{M}{L_1} \text{ (numerically)}$$

$$= \frac{1}{L_1}\left\{\frac{L_1}{m} + \frac{(L_1 + L_2)RCr}{L_1 m}\right\}$$

and, since $\dfrac{1}{\omega^2} = (L_1 + L_2)C$

$$\frac{\text{A.C. voltage on grid}}{\text{A.C. voltage on anode}} = \frac{1}{m}\left\{1 + \frac{Rr}{\omega^2 L_1^2}\right\}$$

but $R/(\omega^2 L_1^2)$ is proportional to the power input to the oscillatory circuit, hence when power in the aerial is zero, either by $R$ being zero or $L_1$ infinite, $Rr/\omega^2 L_1^2 = 0$.

Then $$\frac{\text{A.C. voltage on grid}}{\text{A.C. voltage on anode}} = \frac{1}{m}$$

When maximum power is obtained in the oscillatory circuit

$$L_1 = \frac{\sqrt{(Rr)}}{\omega} \text{ [see Eqn. (11)], whence } \frac{Rr}{\omega^2 L_1^2} = 1$$

Then $$\frac{\text{A.C. voltage on grid}}{\text{A.C. voltage on anode}} = \frac{2}{m}$$

For other powers in the oscillatory circuit the necessary a.c. grid voltage ranges from $1/m$ to $2/m$ times the anode pulsatory voltage.

It must be borne in mind that these values are the minimum at which oscillatory current can be obtained and that they represent conditions in the triode which hold when the oscillatory current through it is sinusoidal. The peak value of the current is just equal to the steady current, and a momentary resulting condition of zero current when there is maximum potential on the anode, as shown in Fig. 5. The operating efficiency is 50 per cent.

At any given power in the oscillatory circuit let the highest value of current in the triode be $i$.

If $i_2$ = the R.M.S. value of the oscillatory current, then $i = 2\sqrt{2}i_2$.

Power to oscillatory circuit

$$= \frac{E_1}{2} \times \frac{R}{w^2 L_1^2} = \frac{E_1}{\sqrt{2}} i_2 \text{ (see previous section)}$$

i.e. $$\frac{E_1 R}{2\omega^2 L_1^2} = \frac{i_2}{\sqrt{2}} = \frac{i}{4} \text{ and } \frac{R}{\omega^2 L_1^2} = \frac{i}{2E_1}$$

But the a.c. voltage on grid is

$$\frac{1}{m}\left\{1 + \frac{Rr}{\omega^2 L_1^2}\right\} \times \text{a.c. voltage on anode}$$

or $$\mu = \frac{1}{m}\left\{1 + \frac{Rr}{\omega^2 L_1^2}\right\} V$$

and $$\mu_{max.} = \frac{1}{m}\left\{1 + \frac{Rr}{\omega^2 L_1^2}\right\} E_1$$

$$= \frac{E_1}{m} + \frac{ri}{2m}$$

However, since the anode pulsates from $+E_1$ to $-E_1$, the total pulsation is through $2E_1$, or through $2E$ when there is only a small current through the triode, and the total pulsation on the grid is $2\mu_{max.}$

Thus the total pulsation on the grid $= (2E)/m + (ri)/m$, while the anode pulsates from $2E$ to zero.

It is to be noted that this is entirely independent of generated frequency or wave-length.

Take first the case in which the current $i$ in the triode is infinitely small, and the aerial current correspondingly small, so that we have what may be regarded as voltage pulsations only. The total grid pulsation $= 2\mu_{max.} = 2E/m$.

Referring now to Fig. 10, in which the characteristics of the triode as shown in Fig. 2 are reproduced, the grid pulsation is represented in magnitude by a length AB which is $= 2E/m$ on the grid voltage scale.

The locus of the voltage pulsations may, in fact, be represented by the line AB, instantaneous values being read off on grid and anode scales respectively. The middle point of the oscillation is X on the grid scale, and $E$ volts on the anode scale, and the oscillation is a pendulum motion in time along AB. The locus AB has no ordinate on the anode ampere scale, thus indicating that no current is passing through the triode. A suitable steady grid potential is represented by a negative value OX.

To obtain the locus of the oscillation when a given amount of power is passing into the oscillatory circuit involving a current $i$ in the triode at its highest value, draw from the zero anode voltage line an ordinate CD representing the current $i$ on the anode ampere scale.

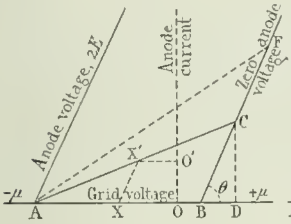


Fig. 10.

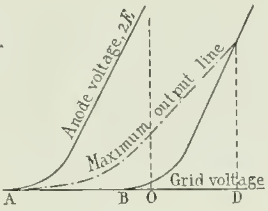


Fig. 11.

Then $i = BD \tan\theta$, where $BD$ is a voltage on the grid scale; but $\tan\theta = m/r$ [see Eqn. (2)], therefore $i = BD \times m/r$, or $BD = ri/m$ volts on the grid scale.

The total grid pulsation is required to be $(2E/m) + (ri/m)$, which is seen to be AB + BD = AD.

The locus of the oscillation can accordingly be represented by a line AC of which the ordinates are instantaneous currents in the triode; with harmonic motion in time the ordinates produce a sinusoidal wave-shape of current. The middle point of the oscillation is X′ and a suitable steady grid potential is a negative value O′X′.

An increase of current through the triode is produced either by reducing the anode tapping inductance or increasing the resistance in the oscillatory circuit as shown previously, but every condition may be represented (when adjusted for an operating efficiency of 50 per cent) by locus lines such as AC or AF.

The grid pulsation at maximum output is shown above to be double that when no current flows through the triode, viz. it becomes 2AB. B is therefore the middle point of the grid pulsation and OB is accordingly the steady grid potential. This condition is, however, not representative of a practical condition; it will be remembered that the argument used in deriving the point of maximum output was based upon the control of the steady potential of the grid by a grid-leak resistance which, perforce, maintains a negative voltage relative to the filament, whereas OB indicates a positive one. It remains, therefore, to explain how it is possible to reach maximum output with a steady negative potential on the grid. The reason is to be found in the fact that the real characteristics of the triode are not exactly the assumed ones in Figs. 2 and 10. A more accurate representation is shown in Fig. 11, in which the bend in the characteristic lines at low current values is emphasized. It is clear from this that in order to stop current flowing through the triode at an anode voltage of $2E$, the grid potential is much more highly negative than has been previously represented. The oscillation line follows more nearly the dotted line of Fig. 11, a considerable departure from a straight line, indicating that the hypothetical alternating current superposed on the d.c. current through the triode has positive and negative half-waves which are unlike. It will be seen shortly that it is desirable to have an oscillating line of this character as it greatly improves the operating efficiency. In any case, to obtain the conditions shown in either Fig. 10 or Fig. 11, in which the triode current is just cut off at the highest anode potential, it is necessary to have independent control of the steady grid potential.

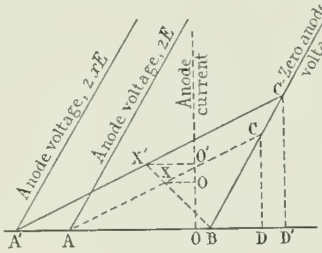


Fig. 12.

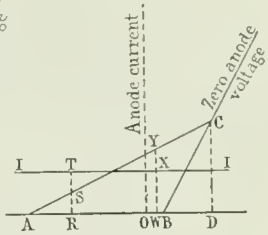


Fig. 13.

Consider next the case of an increased supply voltage, the circuit remaining unchanged except for the control of the steady grid voltage which must be adjusted to produce similar conditions by cutting off the triode current at the moment of peak anode voltage. Let the supply voltage be increased $x$ times; the anode pulsation can then increase $x$ times and with it the aerial current which in turn draws $x$ times the previous current through the triode. The pulsating grid voltage, being proportional to the aerial current, also increases $x$ times. A new oscillation line parallel to the former one is therefore obtained as shown in Fig. 12, all voltages and currents in the diagram being increased $x$ times. The power in the oscillatory circuit and in the triode increases as $x^2$. The steady grid voltage, it will be observed, also requires to be increased nearly $x$ times, a condition automatically fulfilled in general by the use of a grid-leak resistance.

For an oscillation line considered in Fig. 10, the d.c. current drawn from the supply is half the peak value of the current through the triode, and is represented in Fig. 13 by the ordinates of I, I. At the instant represented by the ordinate RST, RS is the current in the triode and ST the current passing through the blocking condenser to the oscillatory circuit, or the component of the hypothetical alternating current passing through the triode, which is the energy current for the oscillatory circuit. At the instant WXY all the steady current WX is passing through the triode, and an additional component XY is the instantaneous return current from the oscillatory circuit.

The alternating energy current passing to the oscillatory circuit is alternately extracted from and given to the triode during each half period. It is, however, extracted when the voltage is high and returned when the voltage is low, so that there is a net extraction of energy as it were from the triode, and, in order to allow of the process being carried on, a steady supply is received by the triode from a separate source.

When the alternating current superposed on the steady triode current is truly sinusoidal in wave-shape it has been shown that the oscillatory circuit receives half the total input from the source. The only way in which a greater proportion of the total power input can be transferred to the oscillatory circuit is to upset the regularity of the cycle by which current is extracted from and returned to the triode from the oscillatory circuit. It is necessary only that $\int idt$ (or the coulombs in one direction) shall be equal to the coulombs in the other direction within one complete cycle. If this were not the case, the anode blocking condenser would begin to charge up with an increasing steady potential. What is required, therefore, is to be able to continue to extract current from the triode when its voltage is high, and return a high value of current in a short period of time when the voltage on the triode is low; the consumption in the triode for a given current is then a minimum.

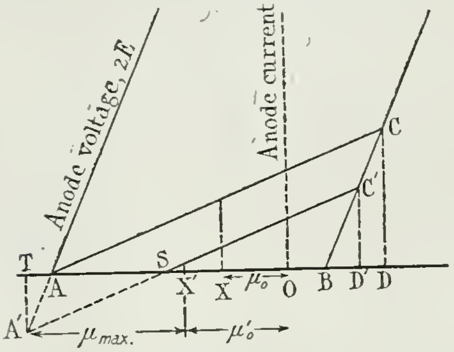


FIG. 14.

With this object in view the effect of changing the conditions imposed on the triode may next be considered. First, let a higher steady negative grid potential be imposed. Assuming that the original oscillatory current can be maintained (a higher one is impossible since the anode is already pulsating from $2E$ to 0), the oscillatory grid voltage remains unchanged, and thus the projection of the new oscillation line on the $\mu$ axis must be the same as before. It is therefore concluded that the new line is parallel to the previous one (see Fig. 14), working between the same limits of anode voltage. The magnitude of $\mu'_0$ being fixed, the position is definite.

A portion of the new line A′S indicates a reversal of current through the triode, but, since the electronic current cannot reverse, all the current through the triode in that portion of the cycle represented by A′S is cut off. The new oscillation line may therefore be ASC′, provided that the power input to the oscillatory circuit has not decreased.

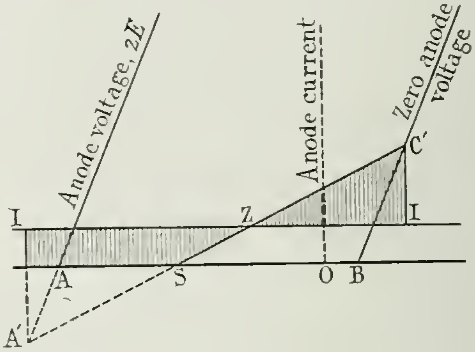


FIG. 15.

Let the current from the source of supply be indicated in Fig. 15 by what must obviously be a reduced magnitude relatively to the previous condition. The point Z which represents the instant of zero current to or from the oscillatory circuit is no longer in the middle of the oscillation. The ordinates of the shaded area IASZ are the instantaneous currents passing into the oscillatory circuit at high voltage and, although the magnitudes are smaller, the time period is longer than before and it is therefore possible for the same power to pass into the oscillatory circuit, while at the same time the consumption of power in the triode itself is much reduced due to current at very high voltages being entirely cut off.

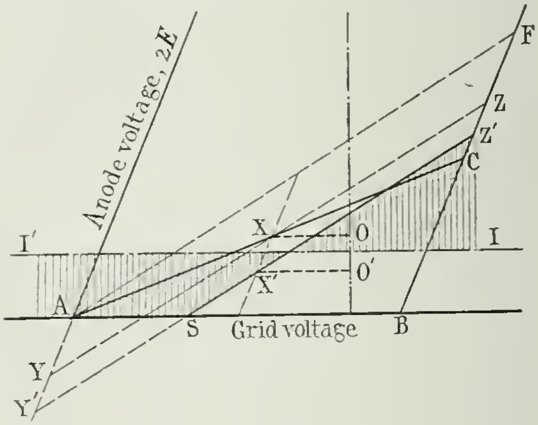


FIG. 16.

The ordinates of ZC′I are the return instantaneous currents from the oscillatory circuit for which $\int idt$ must be the same as in the other sense, but the voltage is much lower and the time for the return of the current is shorter than half a cycle. The net absorption of energy in the oscillatory circuit may therefore be quite as large as in the previous case, and oscillations can be maintained. Throughout the cycle the current through the triode is much reduced, hence there is a reduced power input and an improved overall efficiency.

Gradually increasing the steady grid potential curtails the d.c. current input from the supply and improves the efficiency until the point is reached where the power input is not sufficient to maintain the original oscillatory current, and as this determines a fall in the oscillatory grid voltage which previously was only just high enough to maintain oscillations, the oscillations at this point must cease.

A reduction of the steady grid potential obviously allows more direct current to flow uselessly through the triode and so reduces the efficiency. The oscillation line is parallel to and higher than the original; there is a greater average current in the triode but the oscillatory current remains unchanged.

Now consider the effect of increasing the coupling of the grid to the oscillatory circuit, i.e. increasing the alternating grid voltage. Take the same initial conditions as previously for the basis of comparison, viz. minimum coupling to maintain oscillations and a steady negative potential on the grid sufficiently high to cut off the current through the triode during one instant of the cycle, and so give an efficiency of transformation of 50 per cent. These conditions are represented in Fig. 16 by the oscillation line AXC, where X is the middle point of the oscillation and OX is the steady negative grid potential. The projection of AX on the $\mu$ axis is the peak value of the alternating grid voltage. If now the grid voltage be increased it means that the slope of the oscillation line must be steeper.

It is not possible for a line such as AF to represent the new condition, because it indicates a higher a.c. current through the triode, which can only be brought about by a change in the oscillatory circuit caused by increasing the resistance or reducing the inductance below the anode tapping point. Neither can it be represented by a line such as YXZ having the same mid-point of the oscillation, since there is just the same d.c. current demand from the supply and yet, for one portion of the cycle, current is entirely cut off through the triode so it is impossible for $\int idt$ to be the same for the two half cycles.

Consider next an oscillation line such as Y′X′Z′ which has a higher steady negative grid voltage and also a higher alternating grid voltage than the original line AXC. Due to the higher steady grid voltage the d.c. current input is reduced and therefore, as previously seen, the point at which no current passes from the oscillatory circuit to the triode is no longer the mid-point of the oscillation. It is now possible to obtain the same aerial or oscillatory circuit current at an improved overall efficiency, and a condition may be obtained for which $\int idt$ is the same for both half cycles. It is concluded, therefore, that an oscillation line such as ASX′Z′ is possible. It represents a higher efficiency than 50 per cent. Adjustment of the coupling of the grid coil to the oscillatory circuit is used in practice as a means of regulating the magnitude of the steady grid potential and so arriving at the point of highest operating efficiency.

It is unsafe for most purposes to use an independently controlled steady grid potential, because there are so many conditions which may change slightly and the operating efficiency is so sensitive to changes in grid potential. It will have been noted throughout the paper how admirably suited a grid-leak resistance control is for practical purposes. It responds automatically in the right sense for stability and maintenance of efficient working conditions until the point of maximum output for the triodes is reached.

### Efficiency of Operation.

It is clear that by plotting the instantaneous currents of any given oscillation line on a time basis it is possible to obtain graphically the real efficiency. This has been done by the author in many cases, and it is of interest to note that there appears to be a practical limit beyond which it is impossible to go even when the current allowed through the triode is many times the d.c. supply current, e.g. when the triode is lightly loaded. The limiting efficiency of transformation is approximately 85 per cent.

# EXPERIMENTS ON MODES OF RESONANT VIBRATIONS OF TELEPHONE RECEIVER DIAPHRAGMS.*

By Professor J. T. MacGregor-Morris, Member, and Professor E. Mallett, M.Sc.(Eng.), Member.

(*Paper first received 26th March, and in final form 3rd July, 1923.*)

## SUMMARY.

(1) The well-known phenomenon of the "howling telephone" is extended by the insertion between the microphone and the receiver of a valve amplifier.

(2) The extended phenomenon is used to measure the velocity of sound.

(3) An investigation is made as to which member of the complicated mechanical-electrical system determines the pitch of the "howl."

(4) Sand figures are obtained of some of the various modes of vibration of a receiver diaphragm.

(5) The frequencies of the various modes are compared with those predicted by theory.

(6) Conclusions; that the characteristic note is determined by the telephone receiver, and that the receiver diaphragm overtones are substantially in accordance with the plate theory.

**1.** It is well known that when the receiver of a telephone circuit is placed face to face with the microphone, continuous oscillations may be set up and the telephone "howls"; that is, a continuous note of definite pitch is heard. As the receiver is gradually withdrawn from the microphone the pitch of the note may drop a little before the note dies away. This phenomenon has been investigated by, among others, Mr. F. Gill,† who found that the pitch of the note depended both on the electrical constants and on the mechanical constants of the circuit. For instance, to shunt the receiver with a condenser or to insert inductance into the receiver circuit lowers the pitch; while to add resistance raises the pitch. Also, alteration of the distance between the two diaphragms alters the pitch.

While experiments were being made with a telephone amplifier circuit, the receiver was placed in front of the microphone in the expectation of obtaining a much more vigorous howl. Not only was this successful, but the whole phenomenon was extended in a remarkable way. As the receiver was gradually withdrawn from the microphone the pitch of the note fell and its intensity decreased; without dying away completely there was a sudden rise in the pitch, which again gradually fell as the distance between receiver and microphone increased. After the rise of pitch the intensity of the note was not very great, but became greater as a certain pitch was approached and less after that pitch was passed. That is, there was one note of particular pitch which had the greatest intensity. As the movement of the receiver was continued the whole cycle was passed through again; the sudden change to a high pitch, the gradual lowering of the pitch and increase of the intensity to the most prominent note, and the further lowering of the pitch and decrease in the intensity until the note again suddenly rose. It was observed that the changes of pitch were smaller as the distance increased, and after a time it was practically only the most prominent note that was heard, with silent spaces in between. As many as 18 recurrences of the phenomenon were obtained in this way with a two-stage amplifier. On the receiver being moved towards the microphone the reverse process was gone through; first a rise of pitch, then a break to a lower pitch, with a maximum intensity at a medium pitch. The breaks did not occur at quite the same points as on the outward journey, but the positions for the most prominent note were the same.

It was very soon observed that the distances between the positions of the receiver at which the "characteristic" pitch occurred were approximately equal.

An outline explanation of the phenomenon appears comparatively simple. Suppose that for some reason the microphone diaphragm is vibrating, so that its motion can be represented by $a \sin \omega t$. The motion will produce an alternating current in the electrical circuit whose phase with respect to the microphone diaphragm will change as it progresses through the amplifier to the telephone receiver. Here the current will cause the receiver diaphragm to vibrate, and its vibration will be represented by $b \sin (\omega t + \phi)$, where $\phi$ is the phase difference between the initial vibration of the microphone and the resulting vibration of the receiver, and is due to the various phase changes which occur in the electrical circuit.

Now, the vibration of the receiver diaphragm will cause a sound wave to be propagated towards the microphone, and the phase of the wave on arrival at the microphone will depend upon the distance it has travelled, i.e. upon the distance apart of receiver and microphone. It will, in fact, be given by

$$\theta = - [(l - m\lambda)/\lambda] \times 360$$

where $l$ = distance apart of receiver and microphone diaphragms, $\lambda$ = the wave-length of the note sounded and $m$ = an integer chosen so that $(l - m\lambda)$ is positive and less than $\lambda$. Hence the oscillations of the air in front of the microphone diaphragm are represented by $c \sin (\omega t + \phi + \theta)$. When $\phi + \theta = 0°$ or $360°$ the air vibrations will therefore be in phase with the microphone diaphragm vibrations by which they were initially caused and will sustain the latter if of sufficient amplitude. It is obvious from the expression for $\theta$ that this coincidence of phase will occur at successive positions of the receivers, whose distances apart are $\lambda$.

---

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1902, vol. 31, p. 388.

If now we increase $l$ while a note is being sustained in this way, we increase $\theta$ so that the coincidence of phase at the microphone is disturbed. If, however, the pitch of the note is reduced, $\lambda$ is increased and $\theta$ may be restored to its original value. Assuming that $\phi$ does not alter, the conditions are correct for maintaining a note of lower pitch. Similarly for a movement of the receiver towards the microphone, or a reduction of $l$, an increase of pitch will again correct the phase conditions.

**2.** It would follow from the above that the phenomenon could possibly be used as a method for measuring the velocity of sound. All that we have to do, besides measuring the distances apart of the positions at which the characteristic note appears, the mean value of which gives $\lambda$, is to measure the pitch of the note $n$, and the velocity is found from the relation $v = n\lambda$.

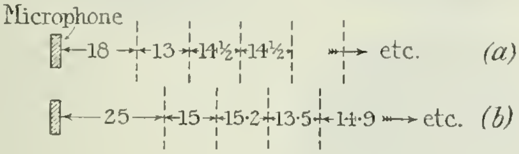


Fig. 1.

An independent source of sound was used so that by means of beats the positions for the required pitch could be obtained accurately, and the pitch was determined by beats with a harmonic of an alternator current passed through a telephone receiver. A difficulty arose in determining definitely which octave was in question, and this was settled by taking an oscillograph record of the current through the receiver of the "howler." The mean wave-length was found to be 14·75 cm, and the pitch of the note 2 284 periods per second, giving $v = 2\,284 \times 14{\cdot}75 = 3{\cdot}37 \times 10^4$ cm per sec. The temperature was 15° C. Correcting for temperature from the formula $V_t = V_0 (1 + \frac{1}{2}\alpha t)$, where $\alpha = 0{\cdot}00367$, we have for the velocity at 0° C. $3{\cdot}28 \times 10^4$ cm per sec., a result within 1 per cent of the generally accepted value.

Further experiments were carried out. For instance, the receiver terminals were reversed. This resulted in the positions for the characteristic note being altered very nearly to midway between the previous positions, as indicated in Fig. 1. (Dotted lines show receiver positions, while (*b*) is with receiver terminals reversed.)

This is just what would be expected from the above explanation, as the phase of the receiver diaphragm is now changed by 180°, and a corresponding change of half a wave-length is necessary in the air column.

Another interesting experiment demonstrated the reflection of a sound wave. The receiver, whose position was now fixed, was pointed away from the microphone towards a large board. Moving the board caused all the alterations of pitch obtained before, but the distances moved were only half (see Fig. 2). This again would be expected, as the sound wave has to travel to the board and back again before reaching the microphone.

Similarly, reflection at an angle is shown in Fig. 3.

**3.** The explanation of the phenomenon of the sustained oscillations has been made from the standpoint of the microphone; we have seen what would happen if the microphone diaphragm were set vibrating. But evidently it is not necessarily the microphone diaphragm that controls the pitch of the characteristic note. Any part of the circuit, mechanical or electrical, that is capable of free oscillations could conceivably control the pitch. The receiver diaphragm, for instance, is probably more lightly damped than the microphone diaphragm, and is more likely to control the pitch. Again, the transformers of the valve amplifier might possibly have a low natural frequency.

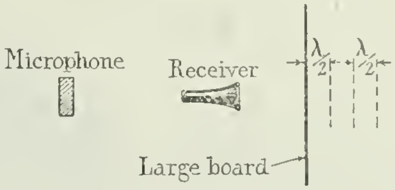


Fig. 2.

At first sight it is not easy to understand why the diaphragm is vibrating at such a high frequency. It is known that the natural frequency of these diaphragms is about 1 000 periods per sec., but the observed characteristic pitch was 2 284 periods per sec. However, it was thought possible that the receiver diaphragm might be vibrating in a higher mode. For instance, vibrating with one nodal circle it would have, on the membrane theory, a frequency 2·296 above the fundamental. Taking the latter as 1 000, this would give for the characteristic pitch 2 296, which compares very well with the value found.

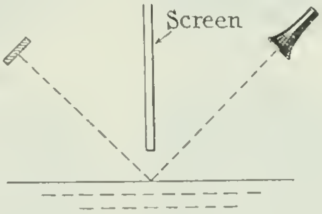


Fig. 3.

To test this point definitely it was necessary to force the receiver diaphragm to vibrate in some other mode. The two poles of the receiver normally, of course, act together, and their dimensions are such that they are well within the first nodal circle. But suppose one of the coils were reversed. Then one pole would strengthen at the same time that the other weakened, and hence one pole would be pulling the diaphragm while the other was letting go, and the tendency would be to develop a nodal diameter. The telephone receiver was altered in this manner; the leads from the two coils were brought out separately so that one coil could be reversed. Four repetitions were now obtained at distances apart of 21 cm, corresponding to a frequency of 1 620 periods per sec. If the fundamental of the receiver were 1 000, the membrane theory would give for the frequency of the one-diameter mode of vibration 1 594 periods per sec., a figure in very good agreement.

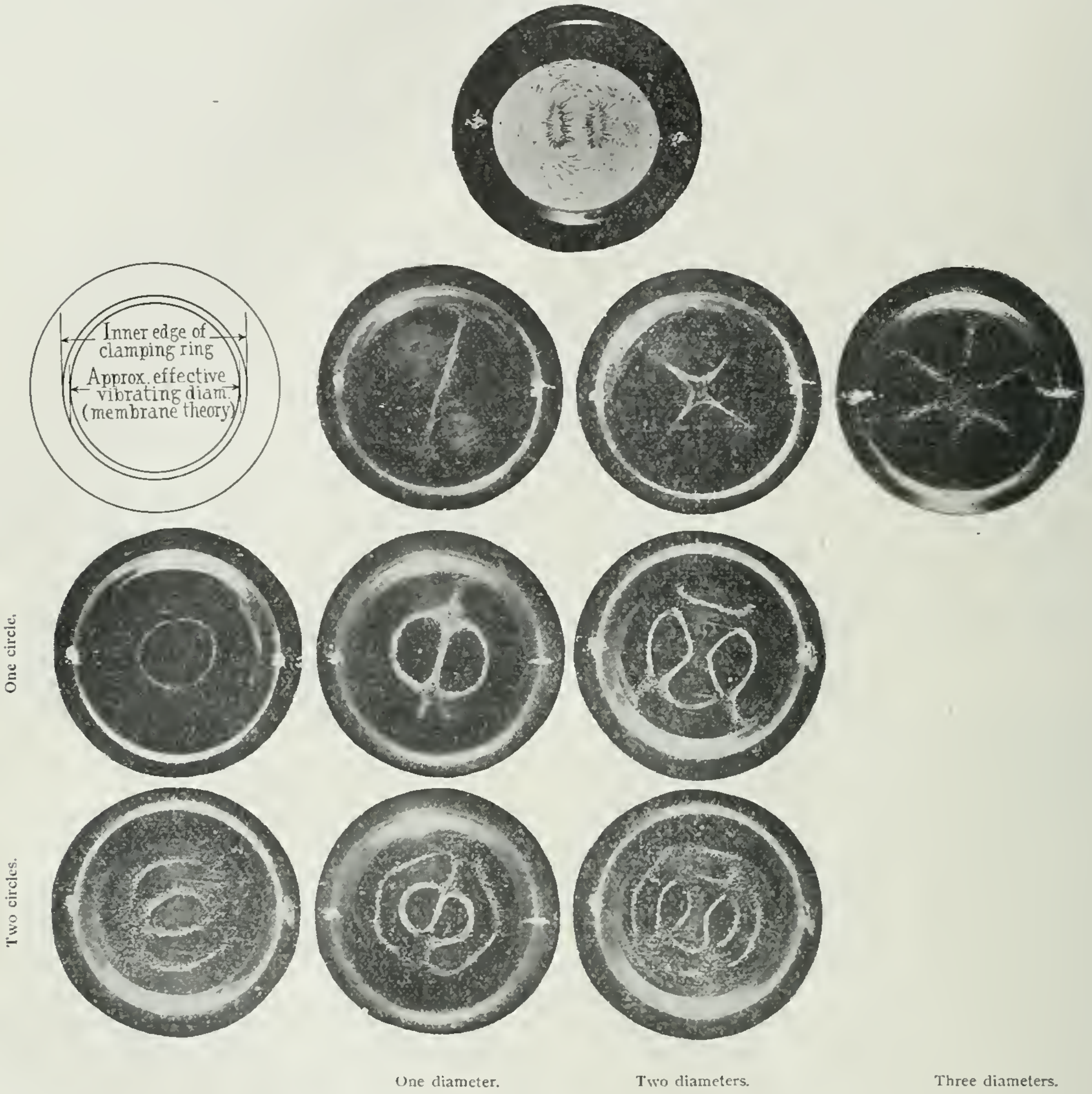

Inner edge of clamping ring
Approx. effective vibrating diam. (membrane theory)
One circle.
Two circles.
One diameter.
Two diameters.
Three diameters.

Fig. 4.

Note.—The "approximate effective vibrating diameter" has been obtained by measuring the average diameters of the visible nodal circles in the above figures, and then dividing them by the ratios of these diameters to that of the outer diameter as given in Rayleigh's "Theory of Sound." The "effective" vibrating diameter for the membrane theory is thus found to be about 8 per cent less than the actual diameter of the inner edge of the clamping ring.

From this it appears extremely probable that the characteristic pitch is controlled by the receiver diaphragm vibrating so as to give an overtone. With the amplifier cut out, the pitch of the note is much lower and probably arises from the fundamental. In this connection mention must be made of a paper (discovered only after the above work had been done) by Kennelly and Upson,* dealing with some similar experiments. They obtained similar repetitions of the variation of pitch by enclosing both microphone and receiver in a tube of variable length; and the characteristic note was the fundamental of the receiver diaphragm.

**4.** In order to be quite certain that the receiver diaphragm could actually vibrate in this manner, the form and position of the nodal lines were examined with the help of sand figures. For this purpose most of the receiver cap was cut away so as to expose the diaphragm, and the receiver was mounted in a stand with the diaphragm horizontal and uppermost, while above the receiver a camera was mounted so that photographs could be taken.

---

* A. E. Kennelly and W. L. Upson: "The Humming Telephone," *Proceedings of the American Philosophical Society*, 1908, vol. 47, p. 329.

The receiver had the four terminals of its coils brought out as described above, and was excited by current from a valve oscillator. The latter was calibrated by reference to a heterodyne wave-meter, heterodyning being obtained with the harmonics of the oscillator.

A very fine foundry sand was sprinkled over the diaphragm and the frequency raised until the sand collected into the desired figure. These figures were quite sharply defined, as will be seen from Fig. 4, and occurred at a very definite setting of the oscillator condenser, so that the frequency was also very well defined. The greatest volume of sound was another method used to define the actual resonant frequency. In the case of the fundamental where, of course, there were no nodal lines, this was the only method available and did not lead to a sufficiently definite value for the frequency. A thermal milliammeter was therefore inserted to measure the current in the receiver, and a curve was obtained connecting this current and the frequency, as shown in Fig. 5. The resonant frequency is approximately $f_0$. In this way the following results were obtained; the receiver coils being reversed in those cases marked *:

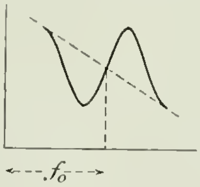


FIG. 5.

TABLE 1.

*Summary of Results.*

| Mode (sand figure) | Frequency, in periods per sec. | Ratio to fundamental |
|---|---|---|
| Fundamental .. .. | 1 050 | 1 |
| *1 nodal diameter .. | 1 630<br>1 420 | 1·55<br>1·35 |
| 2 diameters .. .. | 2 250 | 2·14 |
| 1 circle .. .. .. | 3 000 | 2·86 |
| 3 diameters .. .. | 3 400 | 3·24 |
| *1 circle and 1 diameter | 4 550<br>4 000 | 4·34<br>3·81 |
| *1 circle and 2 diameters | 5 760<br>6 150 | 5·48<br>5·85 |
| *1 circle and 2 diameters | 5 840<br>6 000 | 5·56<br>5·71 |
| 2 circles .. .. .. | 6 820 | 6·50 |
| *2 circles and 1 diameter | 8 600<br>8 150 | 8·20<br>7·76 |

It will be seen that where a single nodal diameter appears there are two frequencies at which the particular figure is produced. The figures were not identical, however; in the second the nodal diameter was always at right angles to its position in the first. It was expected that the nodal diameter would appear midway between the poles of the receiver magnet as in Fig. 6(*a*), but by sprinkling iron filings on the receiver diaphragm to define the poles it was found that it occupied the position shown in (*b*) for one of the frequencies, and that shown in (*c*) for the other. Evidently there was some lack of symmetry which accounted for the difference in frequency between (*b*) and (*c*).

**5.** There are two possible ways of regarding a telephone diaphragm, namely as a membrane, or as a rigidly clamped plate. The theory has been worked out in each case * and results have been given for the ratios of the frequencies of many of the overtones to that of the fundamental. But in the case of the higher unsymmetrical modes, no figures could be found for the plate theory, and for working these out the authors are indebted to Prof. G. S. Le Beau of East London College.

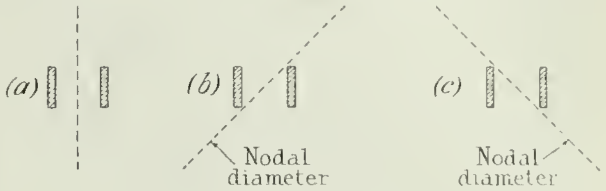


FIG. 6.

These ratios, together with the present experimental results, are collected in Table 2.

TABLE 2.

| Ref. figure | Mode | Ratio of frequency to fundamental: By membrane theory | By plate theory | Experimental (mean) |
|---|---|---|---|---|
| 1 | Fundamental .. .. | 1 | 1 | 1 |
| 2 | 1 diameter .. .. | 1·59 | 2·1 | 1·45 |
| 3 | 2 diameters .. .. | 2·14 | 3·4 | 2·14 |
| 4 | 1 circle .. .. .. | 2·30 | 3·9 | 2·86 |
| 5 | 3 diameters .. .. | 2·65 | 5·0 | 3·24 |
| 6 | 1 circle and 1 diameter | 2·92 | 5·95 | 4·07 |
| 7 | 1 circle and 2 diameters | 3·50 | 8·3 | 5·65 |
| 8 | 2 circles .. .. .. | 3·60 | 8·7 | 6·50 |
| 9 | 2 circles and 1 diameter | 4·46 | 11·7 | 7·98 |

In order that these results may be compared at a glance, they are set out in two graphs (see Figs. 7 and 8) in the following way: In Fig. 7 the ratio is shown vertically against points on the abscissa so chosen as to make the plate-theory points fall on a straight line at 45°. Then the corresponding ratios for the membrane theory and the experimental figures are set out against the same abscissæ, while in Fig. 8 the ratio is referred to the circle instead of to the fundamental.

---

* See RAYLEIGH: "Theory of Sound," vol. 1, chaps. 9 and 10.

It will be seen that, neglecting the fundamental,* there is very good accord between the plate theory and the experimental results.

**6.** The results of the various modes of vibration substantially confirm that the characteristic pitch in the velocity-of-sound experiment was due to the receiver diaphragm vibrating in a higher mode, probably with two diameters.

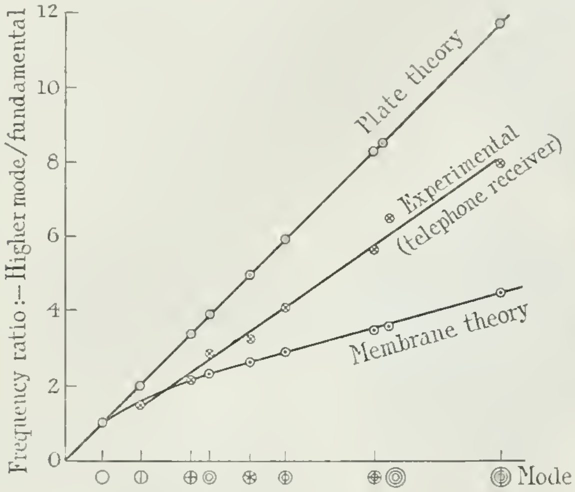


FIG. 7.

The paper lays no claim to completeness, and further experiments suggest themselves in many directions. With a higher-powered oscillator, more and more complicated modes could doubtless be produced, and in a sound chamber properly padded to avoid effects due to reflection from the walls, or in the open, a serious attempt might be made to use the method as a means of accurately determining the velocity of sound. By the use of lightly-damped receivers designed to have various natural frequencies, the characteristic note might be altered at will. Further, a complete investigation of the alteration of the characteristic pitch with the position of the receiver should be made.

Thus it is clear that the work is capable of considerable extension, but it is thought that the results obtained are of sufficient interest for publication. The importance of the higher modes of vibration of a diaphragm in connection with the telephonic transmission of music is obvious. Whereas with speech one can be content to limit oneself to frequencies of the order of 2 000 periods per sec., this is by no means the case with music.

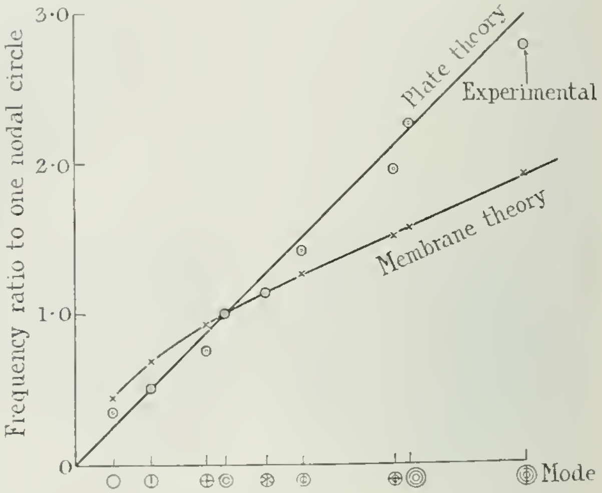


FIG. 8.

The whole of the experimental work was done over two years ago in the Electrical Engineering Laboratories at East London College.

---

* *Note added* 15*th June*, 1923. Later experiments indicate that the working conditions in a telephone have more effect on the fundamental mode than on the higher modes of vibration.

# PROCEEDINGS OF THE INSTITUTION.

## 699th ORDINARY MEETING, 12 APRIL, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.**, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 22nd March, 1923, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

The following list of donors to the Building Fund and Benevolent Fund was taken as read and the thanks of the meeting were accorded to them.

*Building Fund.*—W. M. Mordey.

*Benevolent Fund.*—C. E. Acock, B. N. Adams, D. Adams, G. H. Adams, W. J. Addison, A. N. Aikman, I. M. E. Aitken, W. Aitken, E. O. Alabaster, H. Alabaster, C. D. Alder, G. Allan, P. F. Allan, A. H. Allen, C. W. Allen, T. P. Allen, G. Allom, R. Anderson, A. E. D. Andrews, O. M. Andrews, R. Andrews, Anonymous, A. N. Arman, R. E. Armstrong, C. Arnold, K. N. Arnold, J. Ashmore, R. E. Atkins, Ll. B. Atkinson, W. S. Atkinson, H. S. E. Austin, H. J. Aylott, C. F. Baggaley, A. R. E. Bailey, A. E. Baker, C. J. Baker, W. Baker-Brown, P. E. Bamford, J. Banks, H. Bannister, E. Barlow, A. G. Barnard, A. S. Barnes, F. T. Bartho, H. A. Bastable, D. O. Bates, F. H. Batt, G. R. Battle, H. Batty, H. E. I. Bax, E. H. Baxter, E. J. Baxter, W. Baxter, M. Beales, J. S. Bean, H. P. Bearcroft, A. W. Beaumont, E. A. Beavis, R. Bedford, A. T. S. Beebee, S. Beeton, E. G. Bell, W. A. Benger, A. E. Bennett, C. H. Bennett, H. W. J. Bennett, R. H. Berriman, J. W. Binns, W. Bird, K. W. Birks, D. H. Bishop, R. S. C. Blance, R. F. P. Blennerhassett, E. H. Bond, W. L. Booth, C. A. Boraston, A. F. Bound, F. J. Bown, I. Braby, H. P. Bramwell, C. Brazier, F. W. Brecknell, F. G. Briant, E. E. Briggs, J. C. Briggs, R. E. Bristow, S. K. Broadfoot, J. Brodie, J. A. Bromley, R. C. Brookes, R. P. Brousson, Arthur Brown, Edward Brown, James Brown (M.), James Brown (A.M.), J. S. Brown, R. C. Brown, Walter Brown, William Brown, A. W. Browne, W. H. Brownjohn, R. H. Bryans, H. C. Bullman, V. A. M. Bulow, N. K. Bunn, R. Bunting, P. G. H. Burbridge, W. C. Burbridge, A. F. Burgess, J. Burke, W. E. Burnand, J. Burns, G. B. Burrows, W. Burton, J. M. Butcher, H. C. Calogreedy, D. L. Cameron, H. G. Cameron, P. J. Camozzi, A. C. Campbell, R. H. Campion, H. S. Cannon, A. D. Carden, H. S. Carnegie, J. L. Carr, J. H. Carrick, H. E. Carrott, W. N. Carson, A. F. Carter, E. Carter, J. W. P. Chalmers, D. H. W. Channon, H. C. Channon, C. E. Charman, C. B. Chartres, R. A. Chattock, A. R. Chaytor, G. A. Cheetham, G. G. Chisholm, L. F. Christy, E. F. Clark, J. E. Clark, W. H. V. Clark, G. B. Clarke, B. C. Clayton, P. Clegg, J. K. Clifford-Jones, W. C. Clinton, H. W. Clothier, T. D. Clothier, N. Clough, T. Clutterbuck, F. Coates, G. D. Coe, F. G. Cole, H. F. Colebrook, H. W. Collard, A. Collins, C. F. Collins, W. Collins, C. Collyns, J. B. Colquhoun, A. D. Constable, N. J. Cook, W. W. Cook, H. Cooke-Smith, G. W. Cooper, W. J. Cooper, W. O. Copland, F. W. J. Corbett, A. B. Cousins, R. W. H. Couzens, G. L. Coventon, A. C. Coward, J. R. Cowie, C. H. F. Cox, P. H. Cox, The Hon. E. H. Cozens-Hardy, F. W. Crawter, R. L. Cribbes, C. Crompton, A. F. Cross, S. G. Crowder, C. E. Cruttwell, W. Cuffley, J. F. Dale, I. S. Dalgleish, J. D. Dallas, J. F. F. Dalston, J. C. J. Dalton, B. Darby, F. E. Davies, G. F. Davies, G. H. Davies, James Davies, P. G. Davies, W. Davies, B. M. J. Davis, H. F. E. Deane, F. E. Denné, J. W. Desborough, Sir James Devonshire, T. J. Digby, C. D. H. Dixon, E. Dixon, A. B. F. do Amaral, H. B. Dorrell, H. S. Double, H. M. Dowsett, B. M. Drake, L. Drucquer, C. L. Drury, C. V. Drysdale, L. Dunbar, P. C. Ebner, W. H. Eccles, R. J. Eccleston, K. Edgcumbe, E. A. Edwards, F. S. Edwards, L. Edwards, W. J. Edwards, H. S. Edwin, The Electrical Engineers' Ball Committee (per A. M. Sillar), J. Elias, A. E. Ellis, S. J. Emerson, H. Escott, L. H. Euler, E. W. Evans, G. J. Evans, S. L. Evans, S. Evershed, J. F. E. Farrell, H. Faulkner, S. E. Fedden, W. Fennell, L. G. Fenner, J. D. Ferguson, C. E. Field, H. Field, H. J. Finden, A. J. Flippard, W. D. Fisher, J. G. Fleming, W. K. Fleming, G. H. Fletcher, E. W. Flint, C. L. Fortescue, C. B. Foster, D. S. Foulkes-Roberts, H. C. Fox, H. S. Fox, F. H. Francis, S. Francis, H. W. Franks, W. A. Frazer, B. French, C. A. Friendship, A. Fuchs, J. Galloway, E. Garcke, J. R. Gardiner, J. C. Garnes, J. A. T. Garrard, E. A. Gatehouse, W. H. Gatley, H. P. Gaze, F. A. Geary, F. W. Geoghegan, T. A. George, D. C. Gerrard, H. E. Gibbard, H. J. Gibson, H. W. Gilbert, H. W. Giles, F. Gill, V. W. Gill, M. McA. Gillespie, S. C. Ginno, Sir Richard Glazebrook, L. C. Gleaves, J. B. Glen, H. Gobie, T. E. Goldup, P. Good, M. L. Gorham, E. A. Gordon, L. C. P. M. Grant, P. H. Grant, H. J. Grapes, J. H. Gray, E. Green, Horace Green, J. D. Green, A. C. Greening, F. P. Gresswell, L. Griffiths, W. Griffiths, W. H. F. Griffiths, E. Grime, F. E. Gripper, C. H. Grover, E. E. Grover, H. Guest, W. Gwynn, C. W. Gwyther, B. Hague, R. M. Hale, W. C. J. Halford, P. Hamson, R. Hardy, L. Harley, F. Harris, N. E. P. Harris, H. T. Harrison, A. W. Harrold, W. Harrower, F. de B. Hart, F. N. Haward, F. B. O. Hawes, J. C. Hawkhead, C. C. Hawkins, W. J. Head, W. E. Hedley, V. J. Hegney, J. Henderson, V. P. Henderson, Messrs. W. T. Henley's Telegraph

Works, G. N. Hewett, C. J. Hickleton, J. S. Highfield, W. E. Highfield, W. Higson, E. P. Hill, R. V. Hillman, R. Hills, R. J. B. Hippisley, J. P. Hodges, A. J. Hodgson, W. Hodson, P. M. Hogg, W. Hogg, W. A. Hole, A. S. Hollin, T. Hollins, A. G. P. Holloway, H. Holman, Stratten Holmes, W. T. Holmes, W. Holttum, A. Hooker, J. H. Hornby, W. F. M. Horne, J. W. Horner, W. D. Horsley, R. F. H. Houstoun, A. Howard, A. J. Howard, F. Howard, A. H. Howe, C. T. Hughes, R. G. Hullah, J. A. Hunt, C. G. Huntley, F. W. Hutton, The Informal Meetings Committee (per J. F. Avila), S. Insull, T. Jack, Sir Henry Jackson, E. S. Jacob, E. W. James, W. L. James, W. P. Janes, H. H. Jaques, A. Jarratt, L. G. Jeffery, F. K. Jewson, H. A. Johnson, J. H. Johnson, P. S. Jolin, V. N. Jolliffe, C. Jones, E. Jones, W. E. Jones, S. Joseph, H. J. Kahn, H. F. Kaye, A. E. Keating, D. Keeley, A. C. Kelly, Sir Alexander Kennedy, C. E. Kennedy-Purvis, A. J. N. Kennett, A. Kenworthy, W. T. Kerr, H. Ketton, W. E. Kidner, W. N. Kilner, J. B. Kilshaw, A. W. Kimber, H. Kingsbury, J. E. Kingsbury, J. R. Kingston, H. W. Kolle, H. M. Lacey, G. W. Lambert, H. Lamerton, W. Lang, G. Langdon, A. R. Lash, K. E. Latimer, W. J. Lee, A. Lees, A. H. Leeves, L. J. Lepine, A. E. Levin, W. Lewis, J. W. Lewsley, E. C. Linay, G. Lindley, A. A. Linsell, A. C. Lock, T. H. Lockett, H. Lockwood, A. L. Long, G. Low, A. L. Lunn, W. T. Maccall, J. McCandless, A. McClelland, A. McCord, C. N. McDermott, G. Macdonald, H. A. Macdonald, J. C. Macfarlane, T. McGrath, J. T. MacGregor-Morris, G. M Macilwraith, W. M. Mackay, D. J. McKellar, T. W. E. McKew, P. A. McKillop, J. P. McLare, G. O. McLean, A. I. MacNaughton, H. McNaul, R. F. J. Maidment, F. W. Main, J. B. Mairs, C. W. Mallins, Sir Henry Mance, R. W. Manifold, C. J. Manning, E. Manville, W. B. Marr, F. R. Marsh, W. J. Marston, A. G. L. Mason, D. M. Mason, J. Mason, L. A. Matthews, (Mrs.) Mabel L. Matthews, A. E. May, J. Mayall, R. H. Mead, J. W. Meares, W. B. Medlam, J. D. Meecham, S. W. Melsom, C. H. Merz, R. G. Middlemiss, P. Miley, H. W. Miller, S. C. Miller, A. J. Milne, T. H. Minshall, W. Mitchell, T. J. Monoghan, A. W. Montgomery, R. J. Moore, G. Morath, W. M. Mordey, W. M. N. Morecombe, A. J. Morris, W. M. Morrison, L. R. Morshead, J. A. Morton, C. F. Mounsdon, K. A. Mountain, W. C. Mountain, J. Mullin, J. M. M. Munro, A. R. Murray, G. E. W. Murray, E. A. Nash, C. W. G. Nelson, J. E. Nelson, R. Nelson, G. O. Nevile, C. G. M. New, E. A. Newburn, A. V. Newell, A. S. Newman, A. J. Newman, F. A. Nicholls, E. J. Nichols, J. F. Nielson, C. G. Nobbs, W. B. Noddings, R. J. Nunn, B. H. O'Brien, Sir Andrew Ogilvie, C. Oliver, V. F. M. Oliver, W. Orrell, J. Orringe, F. L. Otter, A. Page, A. H. Palmer, W. G. Palmer, Harry Parker, E. Parry, H. Parry, A. G. Parsons, The Hon. Sir Charles Parsons, G. W. Partridge, W. H. Patchell, W. Pate, C. C. Paterson, H. Paterson, W. H. Patterson, E. L. Payne, F. G. Payne, J. G. Pearce, S. L. Pearce, W. H. Pearce, E. M. Pearson, E. Pellow, D. Pender, S. Pendlebury, S. W. Penney, F. H. Pernet, C. S. Perry, P. Philip, A. G. Phillips, C. G. R. Phillips, S. Phillips, W. A. Phipps, A. Pickersgill, J. W. Piggott, B. J. Piper, J. Piquet, F. C. Platt, W. Pleasance, C. J. D. Pocock, G. E. S. Poland, H. Pollock, W. G. T. Pope, A. E. Porte, F. C. Porte, A. H. Preece, Napier Prentice, A. J. Price, F. E. Price, J. E. Price, L. Price, S. C. Price, T. W. Price, H. F. Proctor, A. P. Pyne, L. Quilliam, G. S. Ram, P. C. Rampe, H. A. Ratcliff, W. R. Rawlings, R. H. Rawll, T. B. Reader, A. C. Reid, R. J. Rennie, T. Rich, F. Richardson, H. W. Richardson, W. P. Richardson, H. A. Rickwood, W. O. Ridley, I. Rigby, R. Rigg, F. Riley, D. Ripley, H. R. Rivers-Moore, D. E. Roberts, J. A. Robertson, R. Robertson, W. H. Robins, B. A. Robinson, C. Robinson, F. W. Robinson, N. H. Robinson, R. T. Robinson, W. M. Robinson, H. J. Rogers, H. K. Rogers, W. R. Rogers, S. R. Roget, T. Roles, A. E. Roots, W. Roscoe, P. Rosling, E. G. Ross, F. A. Ross, G. Ross, W. Ross, G. L. Rosser, F. E. Rowland, A. H. Rowles, L. Rowson, A. Rushton, A. Russell, S. A. Russell, S. G. C. Russell, C. W. Saddington, H. Sampson, H. P. Samuel, G. Sanders, H. R. Sanders, H. S. Saunders, R. Savory, M. G. Say, J. Sayers, T. C. Schneidau, E. W. Scott, G. J. D. Scott, W. H. Scott, F. T. Scragg, E. Seddon, L. J. Sell, F. Shakeshaft, D. C. Sharp, E. E. Sharp, H. P. Sharp, H. Shaw, W. Bolton Shaw, W. L. Shaw, W. Shead, H. C. Shepherd, J. E. Shepherd, G. E. Shires, I. Shirshov, F. A. Simpson, M. G. Simpson, S. Simpson, W. Sinclair, A. K. Sinha, S. R. Siviour, H. A. Skelton, W. R. Skinner, A. E. Slack, J. A. Slee, Sir William Slingo, A. J. Small, E. L. Smith, Gilbert Smith, S. P. Smith, W. F. Smith, W. G. Smith, C. H. Smyth, Sir John Snell, J. B. Snell, H. V. Sothers, J. H. Southern, G. A. V. Sowter, P. G. Spary, W. G. Spencer, S. R. Spruce, R. D. Spurr, W. Stainsby, A. L. Stanton, E. Steadman, W. H. Steele, T. F. Stent, R. M. Stephenson, A. C. Stewart, C. Stewart, Rev. R. H. Streatfield, A. Strickland, H. S. Stride, W. S. Stuart, A. J. Stubbs, H. S. Styan, H. W. Sullivan, W. H. T. Swire, A. L. Tackley, W. C. P. Tapper, J. H. Targett, E. E. Tasker, G. A. Tatchell, C. P. Taylor, F. D. Taylor, H. W. Taylor, W. G. Taylor, F. J. Teago, R. St. G. Terry, V. J. Terry, N. S. Tennant, F. L. Thomas, H. J. S. Thomas, J. Thomas, T. R. Thomas, T. S. Thomas, N. A. Thompson, B. Thomsett, A. Thomson, J. S. Thomson, C. H. R. Thorn, E. W. Thorp, W. G. Tolton, W. E. Tomlinson, W. H. Tranmer, A. Travers, H. W. Tremayne, R. C. Trench, H. F. Trewman, H. Turner, John Turner, J. W. Turner, A. E. Turpin, L. Turton, L. B. Tyler, J. H. Valentine, C. J. Vaughan, C. Vernier, J. A. Vice, A. Vines, J. C. Wade, C. F. A. Wagstaffe, F. Walker, H. P. Walker, Miles Walker, T. C. T. Walrond, A. S. Wann, E. Ward, F. M. Ward, W. L. Ward, E. B. Wardle, F. Wardrobe, J. Waring, J. W. Warr, H. W. Warwick, C. T. Waterhouse, E. W. Waters, F. Waters, E. C. Watson, H. E. Webb, P. D. Webb, R. Webb, W. S. Weir, E. H. Wells, G. E. West, The Western Centre (per T. Hood), J. Wetherell, H. Whewell, R. S. Whipple, A. C. Whish, A. E. White, H. G. White, F. Wild, E. J. Williams, H. Williams, W. R. Williams, A. E. Wilson, D. M. Wilson, G. H. Wilson, N. J. Wilson, W. Wilson, F. H. Wise, W. A. L. Wolf, S. S. Wolfe, H. A. Womack, A. N. G. Wood, A. R. Wood, G. W. Wood, K. L. Wood, W. K. Wood, N. C. Woodfin, C. G. A. Woodford, W. B. Woodhouse, R. C. Woods, C. H. Woodward, E. E. M. Woodward, J. H. Woodward, T. G. Woolley, J. W. Woolliscroft,

C. H. Wordingham, H. G. Wright, J. H. Yates, H. E. Yerbury, H. W. Young, J. J. Young, and W. Young.

Mr. A. G. Warren, M.Sc., Member, delivered a lecture on "The X-ray Examination of Materials" (see page 949); and Mr. G. L. Addenbrooke, Member, then exhibited, on behalf of Mr. E. E. Brooks, a number of lantern slides showing lines of electric force, in connection with which **Mr. Addenbrooke** made the following remarks:—

"These slides were produced from negatives taken in the following way. A camera is arranged vertically over a flat-bottomed glass dish which can be illuminated from below in any convenient way. In the bottom of the dish a ground glass plate is placed and to this are attached pieces of metal in any shape desired to form electrodes. (It is desirable to avoid sharp edges or points as far as possible.) Wires lead from these electrodes to the source of E.M.F., which is usually a Wimshurst machine. The machine is turned gently and the potential of the discharge is kept constant by using a small spark-gap.

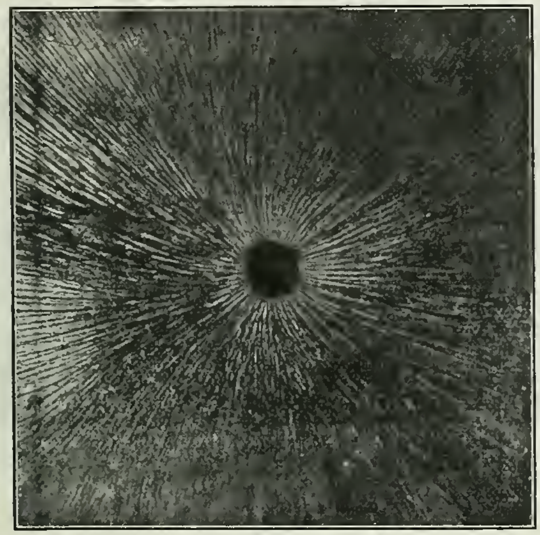


FIG. 1.

"These are the general arrangements. For the purpose of producing the visual indications of the directions of the lines of force in the electrical field as shown in the figures, a sufficient amount of a dielectric liquid, e.g. turpentine, is poured in the dish to cover the conductors to a depth of from $\frac{1}{4}$ in. to $\frac{1}{2}$ in. Some granular material in a fine state of division is then poured into the dielectric liquid and well mixed with it. On applying the field, this material has a tendency to settle along the lines of force, when a photograph can be taken showing exactly what has occurred.

"Some eight or nine years ago Mr. E. E. Brooks, of the Leicester Technical College, after much experimenting with various substances, found that certain of the aniline dyes far outclassed other materials in producing clear and extensive deposits along the lines of force. He finds that only a few dyes behave in this manner, the majority being either inert or giving a very poor field. As a guide to other experimenters it may be remarked that he finds that very frequently the dye acts better after being kept in turpentine for some days. A mixture giving a poor result when freshly made may work well in a week's time. It is best to mix the dye separately in some of the dielectric liquid, stir well and then pour the mixture into the rest of the liquid on the dish. Other investigators have tried similar methods with comparatively poor results. Success evidently lies largely in the use of a suitable material.

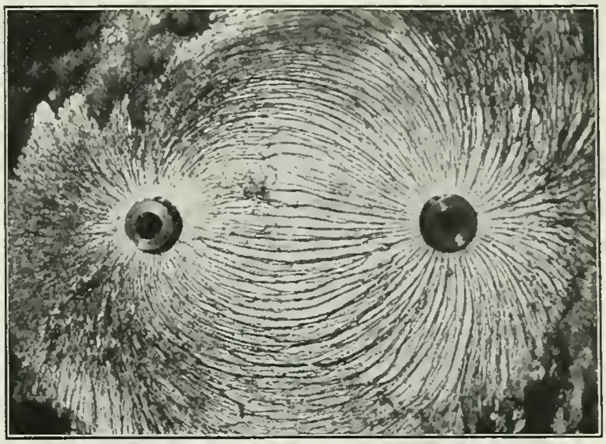


FIG. 2.

"The slides exhibited were obtained by Mr. Brooks in this way, and are reproduced in Figs. 1 to 6.

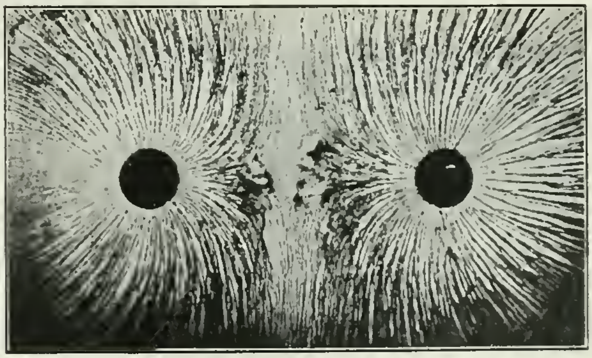


FIG. 3.

"Fig. 1 shows the radial field around a single isolated conductor, the lines radiating to earth equally in all directions.

"Fig. 2 shows the field between two conductors having unlike charges.

"Fig. 3 shows the field between the same conductors but with like charges. (The conductors used were the tops of small brass terminals.)

"Fig. 4 is a vertical section of a hollow, charged metal can. It will be seen how the lines of force stream out from the top, and the peculiar curve that they take, and also that there is no field inside the hollow conductor itself.

"Fig. 5 shows the inductive effect of a charge on an insulated metal conductor near it, and is particularly interesting and instructive.

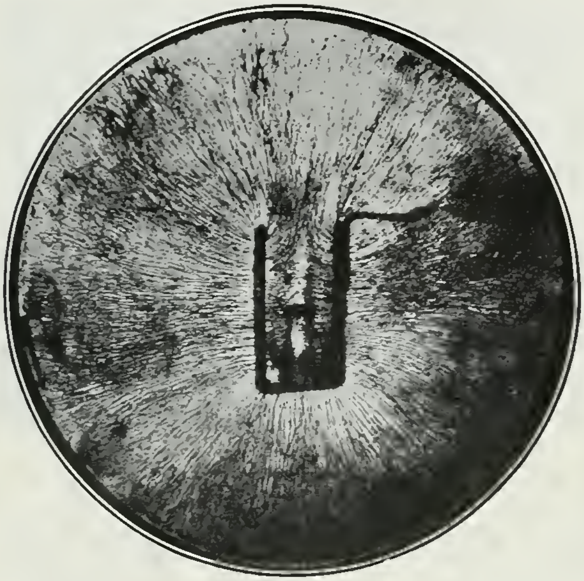


FIG. 4.

"Fig. 6 illustrates the important case of a condenser and the fringe effect at the edges. It is difficult to obtain in this case at the same time a good delineation of the field between the plates and also at the edges, because a convection current of liquid is easily set up which tends to drive away the active material from points and edges.

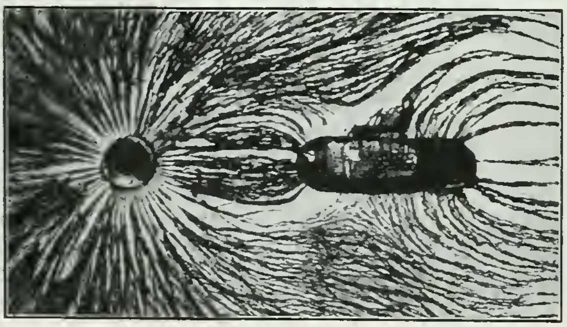


FIG. 5.

"The actions which Mr. Brooks has so well illustrated are occurring all round us whenever there is a difference of electric potential. Hitherto our knowledge of them has been gained from the diagrams originally prepared by Maxwell on purely mathematical and theoretical considerations. Here we have them prepared by Nature herself, and, as far as I am aware, it is the first time they have been obtained with a fair amount of clearness and detail.

"When it is remembered that the view is fast gaining ground that cohesion and all actions in matter, including chemical combination, are due to electrical forces, and that here we have very definite and detailed illustrations of how such forces act, it is clear that these photographs ot Mr. Brooks's are worthy of, and will repay, not only a glance but careful detailed consideration. It seems to me that for the purposes of explaining electric actions and impressing their general character on the mind they have great value.

"(*Communicated*): In a paper on 'The Character of Dielectrics and their Powers of Standing Alternating Electric Stress,' written by me in 1908 but not published, there were the following observations on the same subject from somewhat different points of view which may be useful to intending experimenters; they were at the same time intended to illustrate the general nature of the actions which lead up to breakdown.

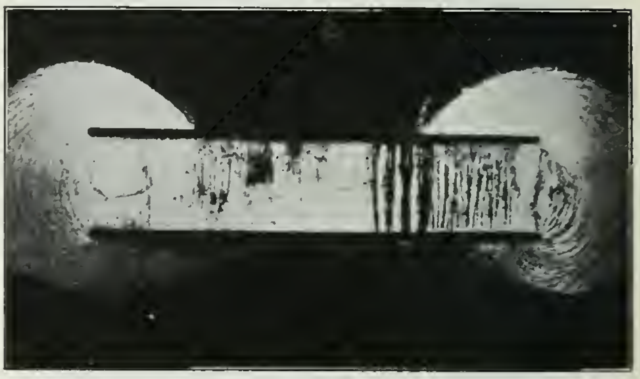


FIG 6

"*Action of an alternating electric stress on a liquid dielectric.*—For this purpose a shallow glass cell was formed which could be strongly illuminated from underneath and which could be observed through a magnifying lens. The cell was filled with mineral oil and a little dust was placed in it. Conductors carrying a current at 1 000 volts and 83 periods were immersed in the oil and arranged so that they could be set at any desired distance apart. As soon as the voltage was applied many of the particles of dust began to arrange themselves in lines radiating from the electrodes and these lines again tended to coalesce into a single line lying in the shortest path between the two electrodes. This chain of particles gradually became thicker by accretion until, if the electrodes were near enough together and the amount of dust in the oil sufficient, a sudden flash and short-circuit took place. Often also, small particles could be seen alternatively attracted to the electrodes and thrown off at a great rate, and reciprocating movement in the chain of particles between the electrodes was observable the whole time, so that the strain always occurred through the oil and not through the air above, showing how much the chain of dust particles must have reduced the disruptive strength of the oil. With direct currents under similar conditions there is a continuous flow of oil from one electrode to the other, forming a regular circulation; with alternating currents this does not occur, but it seems in accordance with theory that in this case any bodies in the field capable of carrying an electric charge should experience an attraction tending to cause them to arrange themselves in the shortest path between the ends of the two conductors. If the conductors were parallel to each other, this would result in a sort of conducting sheet being established between them. It may be also that any free moisture in the dielectric may act in the same way.

"There is evidently a great deal of knowledge of obscure actions to be gained by a further careful study of what occurs in dielectrics in electric fields under such conditions as are outlined above, and I feel sure that the results would be of importance technically as well as scientifically."

On the motion of the President a vote of thanks was accorded to Mr. Warren and to Mr. Addenbrooke, and the meeting terminated at 7.20 p.m.

## 700TH ORDINARY MEETING, 26 APRIL, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 12th April, 1923, were taken as read and were confirmed and signed.

Messrs. H. C. Healey and J. Whitcher were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows:—

### ELECTIONS.

*Members.*

Reynolds, Dr. Russell John, M.B., B.S.
Shea, Joseph.

*Associate Members.*

Barnes, Herbert, B.Sc.
Bryan, George Blackford, B.A., D.Sc.
Evans, Thomas Taylor.
Lund, Arthur.
Pink, Edward Nicholas, B.Sc.
Stirrup, John.

*Graduates.*

Browne, Edgar Whitaker.
Clarke, Charles Richard.
Deveney, Frederick Gordon.
Gatland, Howard Charles.
Goodman, Roi Howard.
Haffner, Howard.
Hancock, Gordon Leonard.
Hurst, Walter Greaves.
Messent, Sydney William, B.Sc.(Eng.).
Morgan, Thomas Cyril.
Norman, Henry Nigel S., B.A.
Potter, Howard.
Rankin, John Teasdale.
Roberts, George Alfred A.
Rogerson, Robert.
Ross, Thomas Wylie.
Shears, Horace Humby.
Siret, Eugene Colbert.
Small, Charles Edward.
Stupart, Gustavus Henry C.
Swensen, Erling.
Tharle, George Victor.
Wilkins, Cecil.

*Students.*

Allsop, David.
Bamber, Leonard John.
Bath, William Wilson.
Brearley, Reginald John.
Brittain, Francis Hugh.
Butler, Hewitt Kenneth.
Cleveland, Harold Arthur.
Comino, Demetrius John.
Dean, Andrew Robertson.
Dowell, William George.
Draper, Brian.
Eckersall, William Alfred.
Ferens, Lionel.
Ferguson, Robert Hugh.

*Students*—continued.

Godfrey, Percy Frederick.
Gover, David Frank.
Guthrie, Thomas Hodge.
Holmes, Reginald Henry.
Honey, Eric Maurice O.
Howard, William Archibald F.
Hulcoop, Frank Albert.
Hunt, Maurice Stanley H.
Inglis, Charles Colin.
Irwin, Arthur Edward.
Johnson, Charles William.
Kadir, Amin Abdel.
McKeown, Henry Percival.
Mahdjoubian, Paul Michel.
Marsh, George Thomas G.
Martin, George Henry R.
Mendelson, John.
Moore, James Leslie.
Morgan, Guy William.
Moss, Richard Douglas P.
Murphy, Patrick Gerard, B.E.
Niven-Clark, Alwyn.
Norris, Harry.
Pilgrim, William Howard.
Rea, John Ralph.
Rossiter, William Gilbert.
Rowson, Robert Bryan.
Salmon, Leslie Bernard.
Savory, Alan Ballantyne.
Shackleton, Ernest Chadwick.
Steels, George Harwood.
Todman, George Richard.
Truman, Leslie Harold.
Wade, Eric Douglas.
Watton, Eric Bernard.
Watts, Donald.
Weare, Henry Owen.
Webber, Maxwell Harry.
Wermig, Harold Leslie.
Whittaker, Harry.
Willett, James Hawley.
Williamson, George David.

### TRANSFERS.

*Associate Member to Member.*

Aspinall, Henry Oswald.
Corson, Frank Huntingdon.
McInnes, Henry Airton.
McKellar, Duncan John.
Peck, George Arthur.
Rodwell, Arthur.

*Graduate to Associate Member.*

Elsden, George Harry.
Pearce, Frederick James.
Plowman, Ashley Sheridan.
Seaward, William.
Witt, Sidney Herbert.

*Student to Associate Member.*

Bayliss, Carol William.
Dawson, Cecil.
Edwards, Llewelyn, M.Eng.
Fleming, Robert Tyndall.

*Student to Graduate.*

Dixon, Arthur, B.Sc.(Eng.).
Edwin, Hugh Stanley.
Farmer, Claude Douglas.
Gresswell, William Finlay.
Hill, Hubert George W.
McLean, Alfred Horatio.

A paper by Mr. L. Breach, Member, and Mr. H. Midgley, B.Sc., Associate Member, entitled "The Drive of Power Station Auxiliaries" (see page 829), was then read and discussed, and the meeting terminated at 7.40 p.m.

## 30th MEETING OF THE WIRELESS SECTION, 2 MAY, 1923.

(Held in the Institution Lecture Theatre.)

**Professor G. W. O. Howe, D.Sc.,** Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 11th April, 1923, were taken as read and were confirmed and signed.

The Chairman reported that the following members had been nominated to fill the vacancies which would occur on the Wireless Section Committee on the 30th September, 1923: Mr. E. H. Shaughnessy, O.B.E. (*Chairman*), Mr. C. F. Elwell; Prof. G. W. O. Howe, D.Sc.; Admiral Sir H. B. Jackson, G.C.B., K.C.V.O., F.R.S., and Mr. C. F. Trippe.

A paper by Professor C. L. Fortescue, Member, entitled "The Design of Inductances for High-Frequency Circuits" (see page 933), was read and discussed, and the meeting terminated at 7.50 p.m.

## 701st ORDINARY MEETING, 10 MAY, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 26th April, 1923, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

Messrs. F. B. O. Hawes, P. M. Baker and H. Brazil were appointed scrutineers of the ballot for the election of new Members of Council.

**The President:** I wish to make an announcement in regard to the War Memorial Fund. Out of the balance of that Fund it has been decided to establish two Scholarships, each of the value of £50 per annum and tenable for three years, to provide for the education of children of members who were killed or permanently disabled in the late war. Applications, giving full particulars as to general and financial circumstances, should be addressed to the Secretary of the Institution.

This evening, on the occasion of the presentation of the Faraday Medal to Sir Charles Parsons, and the delivery of the Fourteenth Kelvin Lecture by Professor J. A. Fleming, we are honoured with the presence of Sir Charles Sherrington, President of the Royal Society; Sir Charles Morgan, Vice-President of the Institution of Civil Engineers; Sir John Dewrance, President of the Institution of Mechanical Engineers; and Sir John Biles, Vice-President of the Institution of Naval Architects. So there are present the representatives of the four Founder Societies—the Institution of of Electrical Engineers is the other—of the Joint Engineering Council. Then, in addition, we have Mr. Johnson, representing the South Wales Institute of Engineers; Major-General Sir William Liddell, representing the Institution of Royal Engineers; Sir Archibald Ross, representing the North-East Coast Institute of Engineers and Shipbuilders; and Mr. H. E. Yarrow, representing the Institution of Engineers and Shipbuilders in Scotland. I think that their presence is a tribute to the work we have now to do and to the merit of Sir Charles Parsons.

**Mr. J. S. Highfield:** It is a very real pleasure to speak at the presentation of the Faraday Medal of this Institution to Sir Charles Parsons. When last year I had the honour, as your President, to announce the first award of the Faraday Medal to Oliver Heaviside, I said that I was sure, as time proceeded, the value of the Medal would be enhanced by the illustrious names of those who earned it. Swiftly has that prediction been fulfilled. The name of Parsons ranks among the first engineers of all time. In speaking of him I speak as a humble student at the feet of a master, and yet that master is himself a most earnest student. I think that one essential mark of genius is the persistent retention of childhood's curiosity, the power still to see things as they are and not as we were told they are. When all ordinary engineers were thinking of steam as exerting pressure, Sir Charles Parsons thought of it as a steady rushing expanding wind; his patent specification of 1884 reveals this secret. It is an instance of how every now and then a master hand opens magic windows for us all, admitting a clear new air to use and enjoy if we may. But Sir Charles Parsons did not stop at opening windows; by rare persistence he converted the toy of Hero of Alexandria into the mighty engine for the production of power we know to-day. It is not easy to realize the determined constancy of purpose required to produce this result. Consider alone the vast amount of experimental work carried out during the period of some five years when by an unfortunate mistake he was deprived of the use of his parallel-flow system. Think of the difficulties of the adventure, the anxiety, the great cost and then, finally, the pleasure of achievement. The use of the turbine at sea was realized in the wonderful vessel the "Turbinia" which, apart from the turbine engines, embodied many now well-known innovations. The performance of this vessel of 100 ft. length which achieved speeds over 30 knots is an instance of unexampled progress at one single giant stride. Not the least interesting incident was the voyage from the Tyne to Cowes and back under the command of C. J. Leyland, with her inventor as chief engineer and, I believe, chief stoker too. Apart altogether from the world-famous invention of the steam turbine, Sir Charles Parsons's contributions to scientific discovery are many; a mere recital is here of no avail. Even since the war he has shouldered the responsibility of developing the very important industry of the manufacture of optical glass and optical instruments. Time permits not of further words from me. It suffices that in awarding the Faraday Medal, the highest honour it is in the power of this Institution to offer, to Sir Charles Parsons, the Council are honouring one whose name adds lustre to our membership. May he live long to enjoy the fame his achievements have won and, which I know he values far more, the regard and affection of his many friends.

**Dr. S. Z. de Ferranti:** We have here to-night a distinguished audience, and, as Mr. Highfield has said, every one should know of the great work that Sir Charles Parsons has done. But I am afraid that even we here, who may be called experts in our respective lines of engineering work, do not realize the full extent of his work. He has revolutionized the production of power from coal. Before his time the prevailing idea was that reciprocation was necessary in order to get work from coal. He had the boldness to see, to believe, that that was an indirect process, and that by adopting a process much more direct and efficient he would obtain immensely better results. In connection with this, I may remind you that the reciprocating principle, so far as our knowledge goes to-day, appears to be most suitable for small powers, and the turbine principle for large power. In other words, it is much easier to make a rotary machine efficient when it is made on a large scale, and yet Sir Charles Parsons of necessity had to start with a very small turbine to work out and demonstrate his ideas, and it was only after years of work that he was able, having obtained the necessary knowledge, to develop the larger machines which showed the full utility of the turbine principle which he had developed. The electric motor is a rotary means of obtaining power for useful purposes, and its success is very greatly due to the fact of its great simplicity and of its being practically a single running piece machine. It runs by itself; it suffers very little deterioration, that is to say, it goes on doing the work it has to do without continual cost for repairs, and for those reasons it is in the position it occupies to-day. Now the steam engine before Sir Charles Parsons took the question in hand was in every case reciprocating. The very early engines, even when used for pumping water, did not possess a flywheel. Many inventors endeavoured to get something of the nature of a rotary engine, but in every case it had reciprocating parts. Sir Charles boldly determined to produce a machine which was purely rotary, and to this, to a very great extent, are due the wonderful results that have been obtained. Now wherever we look we shall find evidences of the turbine and the work that has followed in its train. We must remember this: no great discovery was ever made without a great deal of work being put into it. There was very great merit in the idea of the turbines conceived by Sir Charles; but that was as nothing, to my mind, in comparison with the merit which he showed in working it out to a successful issue. The value of a discovery is what it is worth, and when we come to think of what this sort of thing is worth, in labour saved, in the things that we are enabled to do that we could not otherwise have done, we begin to see the meaning of the work that has been necessary to produce them. I do feel that, great as the idea was in its conception, we must feel ever so much prouder of Sir Charles for what he did in working it out to a successful issue that has given us such great benefits.

**The President:** To-day is one of special significance and meaning to electrical engineers, and I desire to add my tribute of admiration to the work which Sir Charles Parsons has done, work so world-wide in its appeal and in its application, and, as regards prime movers, so brilliant that it is liable to blind us to his other excellent work. In vision, in scientific skill and in persistence against enormous difficulties (all those qualities in fact which show engineering in its best sense), Sir Charles has shown a high example to all the engineers of the world. The Faraday Medal was so named in honour of Michael Faraday, the founder and the father of electrical engineering—a name to conjure with among all electrical engineers, no matter from what country they come. The Faraday Medal is awarded "for notable scientific or industrial achievement in electrical engineering, or for conspicuous service rendered to the advancement of electrical science, without restriction as regards nationality, country of residence, or membership of the Institution." You will thus see that it is open to the world, and it is only awarded by the Council of the Institution after most careful examination of those proposed for the honour. Before I present the Medal—the award has already been made by the Council—I feel sure that I am right in calling for the endorsement of this meeting to the Council's action. May I take it that I have that assurance? [The members present unanimously signified their approval.] Sir Charles Parsons, I present to you this Medal, being the second award of the Faraday Medal, conferred by the Council of the Institution in recognition of your most notable achievements for the engineering industry. We are fully confident that you will worthily uphold the dignity and honour of the Medal and of its holders, and we hope that you will live many years in which to enjoy the very special position of regard and affection of all members of this Institution which you hold by right of your own personality and by right of the award of this Medal.

**Sir Charles Parsons:** Words are quite inadequate to express my very deep appreciation of the honour which the President and the Council of this Institution have conferred on me. I felt at first that it might seem inappropriate that the Faraday Medal should be conferred on an engineer, but I have lately been reading

Bence Jones's "Life of Faraday," and I find that Faraday's work was very widespread. He worked for a year or two on the metallurgy of alloy steel, and then was employed for a similar time on the manufacture of optical glass. I think I may perhaps venture to say that all young engineers would do very well to read Bence Jones's work. I should like to quote two extracts, which I think are unique in English literature. The first paragraph is contained in Faraday's Lecture on the Forms of Matter to the City Philosophical Society in 1819, when he was 27 years of age: "The disagreeable and uneasy sensation produced by incertitude will always induce a man to sacrifice a slight degree of probability to the pleasure and ease of resting on a decided opinion, and where the evidence of a thing is not quite perfect, the deficiency will be easily supplied by desire and imagination. The efforts a man makes to obtain a knowledge of nature's secrets merit, he thinks, their object for their reward; and though he may, and in many cases must, fail of obtaining his desire, he seldom thinks himself unsuccessful, but substitutes the whisperings of his own fancy for the revelations of the goddess." Many of our scientists indeed are prone to jump to conclusions too quickly. At the termination of Bence Jones's book these paragraphs occur: "As a man, the beauty and the nobleness of his character was formed by very many great qualities. Among these the first and greatest was his truthfulness. His noble nature showed itself in his search for truth. He loved truth beyond all other things; and no one ever did or will search for it with more energy than he did. His second great quality was his kindness (*agapê*). It was born in him, and by his careful culture it grew up to be the rule of his life; kindness to everyone, always—in thought, in word, and in deed. His third great quality was his energy. This was no strong effort for a short time, but a lifelong lasting strife to seek and say that which he thought was true, and to do that which he thought was kind."

Professor J. A. Fleming, M.A., D.Sc., F.R.S., then delivered the Fourteenth Kelvin Lecture entitled "Problems in Telephony, Solved and Unsolved" (see page 613). A vote of thanks to the lecturer, proposed by Sir Oliver Lodge and seconded by Dr. W. H. Eccles, was carried with acclamation and, Professor Fleming having briefly replied, the meeting terminated at 8.5 p.m.

## 51st ANNUAL GENERAL MEETING, 31 MAY, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 6 p.m.

**The President:** Before dealing with the ordinary business we have the presentation by Mrs. Thompson of the oil painting of the late Prof. Silvanus P. Thompson, the presentation of the Silvanus P. Thompson Memorial Library by Mr. Mordey, and finally the presentation by the Finsbury Technical College Old Students' Association of the bust of Prof. Thompson.

**Mrs. Thompson:** I have very much pleasure in presenting this portrait of Prof. Thompson to be hung in the Institution Library. It was painted when he was 40 years of age, and I am afraid it gives him a more juvenile appearance than that by which most of you are accustomed to remember him. It was painted in 1891, the year in which he was elected a Fellow of the Royal Society and about the time when he made his best contributions to electrical science in connection with dynamos and magnetos, which were then just coming into general use throughout Europe. It was really the time of greatest activity during his life.

**Mr. W. M. Mordey:** I must resist the temptation to-night to speak of Thompson as a man, as a teacher and as a friend. His life and works speak and will continue to speak for him. To-night, in particular, this meeting speaks for him. My duty is the more formal one of giving an account of our stewardship in the matter of the Thompson Library. When Thompson died in 1916, he left a very important and well-known collection of scientific books, mostly electrical. This Library comprised many very early works of great interest and value. When it became known that it would be possible to obtain this Library it was felt that there could be no better memorial of Thompson and a movement was started to purchase the Library and present it to the Institution, of which he was one of our most honoured Presidents. This was a spontaneous movement by friends and admirers of Thompson and of his work and influence, a large proportion being members of the Institution. The Institution showed its interest in and sympathy with this movement which it supported in a very substantial way, but the matter was not inaugurated or carried through by the Institution. A committee was formed on which representatives of the chief scientific and technical societies served, Sir Joseph Thomson representing the Royal Society. A guarantee fund was formed and there was an immediate and satisfactory response. The Institution decided that it would devote to this object such a sum as they would in any case have allocated to a memorial to Thompson, a sum equivalent to that which had previously been devoted to the Kelvin Memorial. Contributions were very numerous, and included subscriptions from many friends who were not directly associated with this Institution or even with electrical engineering or electrical science—friends and admirers of Thompson and members of other Societies. A good many manufacturing firms also made substantial contributions to the Fund, marking their sense of the practical value of Thompson's work. A pleasing circumstance was that the Finsbury Old Students' Association—Thompson's old students—sent a substantial donation. For carrying through the business four trustees were appointed: Mr. Kingsbury, Mr. Campbell Swinton, Mr. Charles Sparks (then President of the Institution) and myself. Early in

1917 we felt we were justified in arranging that the Library should be placed under the charge of the Institution, and it was moved into this building. By the middle of that year the building was taken over by the Government for war purposes, and the Thompson and Ronalds Libraries of the Institution were stored away for safety. Although the purchase was completed in 1918 when sufficient funds had been received, it was not until July 1921 that we actually got possession of the Library and it was temporarily placed on shelves in the Institution Library. Under the terms of the Deed of Purchase the Institution has made permanent arrangements for housing the Library as a separate entity—it is placed at one end of the Institution Library. Although the Library has been at the disposition of members for a considerable time, it was decided that it would be well to deal with the presentation formality on such an occasion as has arisen to-night, when a bust and portrait of Thompson are being presented by others. It only remains for me now, on behalf of the subscribers to the Thompson Memorial Fund, formally to present the Thompson Library to the Institution as a perpetual memorial of one of our most esteemed members and Past-Presidents, Professor Silvanus Phillips Thompson.

**Mr. J. E. Raworth :** During the 30 years that Prof. Thompson was connected with Finsbury Technical College, some thousands of students were trained by him as electrical engineers, many of whom are connected with this Institution. The Finsbury Technical College Old Students' Association felt that they would like to institute a memorial to their old chief. For that purpose funds were collected, some of which, as has been mentioned, were allocated to the purchase of Prof. Thompson's library. The remaining portion was employed in providing a bust which has been executed by Mr. Gilbert Bayes, who is with us this evening, and who was a colleague and friend of Prof. Thompson in the early days of Finsbury. I have very much pleasure in presenting to the Institution this bust on behalf of the Finsbury Technical College Old Students' Association, and I hope that it will be accepted in the spirit in which it is offered.

**The President :** The Institution is deeply grateful for these gifts which have been generously made to it—grateful not only because of their intrinsic and artistic merits, not only because they remind us of one who, while he was with us, was one of our most esteemed and loved members and became one of our honoured Past-Presidents, but grateful also because the donors have chosen this Institution, rather than some other institution, for these gifts and so to link us with the association of his memory. These memorials will constantly remind us of one who, out of a singularly gifted mind, faithfully served his fellow men without stint, as one who had learned to labour and not to look for reward save knowing that he had accomplished his duty. The Institution will, with diligence, cherish and take care of these gifts to the lasting memory of him in connection with whom they are presented. We have with us to-night Prof. Elihu Thomson from the United States, and I feel that I shall be meeting your wishes if I now ask him to say a few words.

**Prof. Elihu Thomson :** I am, I think, fortunate to be present on this occasion which means so much to me as well as to every man who was early in the electrical work and who knew the contributions made by Dr. Silvanus Thompson to the literature and the progress of our favourite industry as well as our science. I think there was scarcely any man who was closer to me in the art than Dr. Silvanus Thompson. The one thing that perhaps drew me more to him than other things was his versatility. He not only succeeded in work which was purely connected with the electrical profession, but he was an optician, a musician and an artist. In my own feeble way I have followed in his footsteps. The last time I met Thompson was under the auspices of the International Electrotechnical Commission, of which I was President, at Turin in 1911, and there I also had the pleasure of meeting his charming wife, Mrs. Thompson. I should like to add a few words in regard to his writings. They are treasured by every student of electricity, and I know that his little manual entitled "Elementary Lessons in Electricity and Magnetism" is still the best that can be recommended for anybody beginning the study of electricity.

**The President :** That concludes the business connected with the presentations, and we shall now proceed with the ordinary business.

The Notice convening the Annual General Meeting having been taken as read, the minutes of the Ordinary Meeting of the 10th May, 1923, were also taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

Messrs. H. W. Couzens and P. M. Baker were appointed scrutineers of the ballot for the election and transfer of members and, at the close of the meeting, the result of the ballot was declared as follows :—

### ELECTIONS.

*Members.*

Mohring, Albert Edward.
Morris-Airey, Harold.
Raven, Sir Vincent Litchfield.
Taylor, Herbert.

*Associate Members.*

Bartlett, Oswald Alfred.
Cursett-Sutherland, P. D.
Daniel, Claude Reginald.
Denman, Roderick Peter G., B.A.
Duncan, Robert Arthur S.
Dunn, Ernest Edward.
Favell, Frederick.
Hamilton, James.
Hinton, Norman Pullen, B.Sc.
Jacquest, Arthur Harold.
Johnson, Charles Valentine.
Macnee, Kenneth William, B.Sc.(Eng.).
Michelli, Capt. Pietro Frederick M., R.E.
Sennett, Harry Hubert.
Swift, Harry Houghton, B.Eng.
Swithinbank, Joseph William.
Whitworth, Harold.
Young, William Ernest.
Yule, John.

### *Graduates.*

Batham, Guy Symonds, B.Sc.
Buchanan, George Macdonald.
Charlton, Thomas Hadwen.
Cook, John.
Dallow, Norman Richard.
Emsley, Albert Edward.
Etches, George Bernard.
Evans, Bertram George.
Fraser, John Andrew.
Hoyle, Frank Conquest.
Hyland, Frank George.
Jones, Elvet Oscar.
Jones, John Charles.
Kolar, Ramchandra Rao.
Kyte, Sydney.
Llewellyn, Frederick Langhorne.
McLennan, Grant A.
Mandlik, Gopal, B.Sc.
Mathews, Edward Daniel K.
Morris, Samuel Henry.
Murray, Robert Lambert.
Nagabushanam, S.
Newland, Horace.
Rhind, Andrew.
Russell, Victor James S.
Sulston, Leonard Edwin.
Webber, Harry.
White, Crawford Gordon.
Wilson, Maurice.

### *Students.*

Abaza, Mohammed Shoukry H.
Adkins, Harry, B.Sc.(Eng.).
Allen, Robert Girdlestone.
Andress, Philip.
Baig, Asaf Ali.
Bailey, John William.
Baines, John William.
Barraclough, Edgar.
Billington, Robert Cyril.
Birth, Arthur Frederick.
Bishop, Edgar Richard.
Booth, Charles Frederick.
Bower, Dudley Alec.
Brand, Frank.
Campbell, Rodolphe William C.
Capon, Leslie Walter P.
Carey, Hewett Clive.
Carter, Herbert Louis.
Charters, Herbert Christopher.
Cooper, Paul Edmund D.
Crabtree, Harold Ashworth.
Craig, John Lawrie W.
Cuthbert, Geoffrey Townley.
Dahl, Gustavo.
Davenport, Arthur Egbert.
Davis, Percival Kingsley.
Devis, Eric Roberts.
Doel, Henry Ernest.
Dunstan, Frederick Percival.
Emanuel, Reginald Rees P.
Farnlund, Harold.
Fitzgerald, Patrick Desmond.
Franklin, Cyril Montagu E.
Gibson, Robert Thomas.
Grover, Ralph Vickers.
Harmer, Aubrey.
Harrison, Ronald John.
Harvey Raymond Edward.
Healy, John Quarry.
Henderson, Douglas Hedley P.
Hill, Adrian Justley.
Hinds, George Alfred R.
Hopwood, Charles Maitland.
Humphrey, Edward Frank.
Husbands, Leslie William M.
Jackson, John Greenville.
Jones, Arthur Stanley.
Jones, Ernest Thomas Lucas.
Jones, Leslie Keene.
Kamen, Cecil.
Kar, Lalit Mohan.
Keane, John Cecil B.
Keith-Murray, Patrick Ian.
Kidd, Lionel Jervis.
King, Alfred Frederick.
Lattey, Louis Douglas.
Lloyd, John.
Lucas, George Sail C.
McCammond, Arthur Norman W.
Macdonald, Ernest Charles I.
McKie, Harold Robert.
Mackill, Robert.
Martin, Algernon John H.
Mather, Frank.
Moore, Douglas.
Moore, Samuel, B.Sc.(Eng.).
Morley, Edward William L.
Nelson, Robert Quentin.
Nunn, Charles Herbert.
Paine, Roger Charles.

### *Students*—continued.

Pilcher, Cecil Walter.
Pinhorn, Ronald Vincent F.
Purden, Robert Hesketh.
Riach, David.
Richards, Cecil William.
Sandeman, David Grant, B.Sc.(Eng.).
Skinner, John.
Smith, Frank Ellis.
Smith, John.
Styles, Sidney Vincent.
Tanner, Herbert Douglas.
Thornton, Cecil Anderson M.
Tomkinson, Alfred Hugh E.
Vinehill, William Francis.
Waite, Barry.
Walker, William Gordon.
Walton, Frank Edward.
Weatherdon, Frank Edwin.
Wells, Arthur Cecil.
Williams, Arthur Avery.
Winnard, Ronald.
Worsp, Lewis Croyden M.

### *Associate.*

Ryan, William Albert.

## TRANSFERS.

### *Associate Member to Member.*

Allan, Colby Topp T.
Bramwell, John Thomas.
Lee, Albert George, M.C., B.Sc.
Malden, Major Charles Horace, R.M.L.I.
Preston, Kenneth.
Saunderson, Philip Sydney.

### *Graduate to Associate Member.*

Featherstone, Henry.
Forsyth, John Cossar, B.Sc.(Eng.).
Gosden, Richard.
Gwynn, Percy Harold.
Lythgoe, Joseph.
Minton, William John.
Morris, Charles Isted.

### *Student to Associate Member.*

Body, Howard Thomas.
Cook, Francis Ainsley.
Gee, Colin Brooke.
Hart, Morris Daniel.
Henderson, Frederick Ewart.
Herriot, David Robertson.
Kingaby, George William.
Richardson, Walter.

### *Student to Graduate.*

Barrington, Reginald Jack C.
Baxter, William Morley.
Fiander, Charles Mac.
Flint, Eustace William.
Kingsbury, Derrick.
Lisle, George Stanley.
Mabbott, William Henry L.
Marchand, Bernard, B.A.
Painton, Claude Arthur.
Pitt, Frank Ernest.
Regis, John.
Thornton, Cecil Victor.

### *Associate to Associate Member.*

Johnstone, Edward Astley.

The following list of donors to the Benevolent Fund was taken as read and the thanks of the meeting were accorded to the donors.

*Benevolent Fund:* W. F. Andrews, A. S. Barnard, D. E. Bell, J. R. J. Bowden, W. Brumwell, W. M. H. Butcher, A. S. Campbell, G. W. Carpenter, R. L. Cleaver, W. A. Coates, H. W. Cockerill, J. Colquhoun, C. F. Crymble, E. Cunningham, A. E. Dawson, Diesel Engine Users' Association, A. E. Dinham-Peren, W. H. Duncan, C. J. A. Ellis, F. J. Gerrard, C. Hamilton, H. Hayhurst, T. B. Hayton, H. J. Henwood, D. B. Hogg, G. Hunter, H. K. Hunter, P. Hunter-Brown, Incorporated Municipal Electrical Association, C. J. Jewell, C. D. King, H. C. Lamb, W. H. Lea, J. H. Leigh, Metropolitan-Vickers Electrical Co. (per Mr. J. Frith), E. H. Miller, R. O. B. Neil, B. Paul, J. D. Peattie, A. J. Ramsay, E. S. Ritter, A. Roberts, G. M. Sichel, M. G. Simpson, J. E. Storr, T. D. Trees, L. E. Ward, J. W. Williams, and G. W. L. Wooland.

**The President,** after summarizing the Annual Report of the Council for the year 1922–23 (see p. 594) and replying to comments by Mr. F. W. Purse, Mr. J. W. Meares, Mr. H. J. Cash, Dr. S. P. Smith and Mr. Ll. B. Atkinson, moved "That the Annual Report of the Council for the year 1922–23 as presented be received and adopted." In the course of his remarks the President mentioned that the Council had decided to reduce the subscriptions of Corporate Members by 10s. per annum and of Graduates by 5s. per annum, the decreases to take place from 1st January, 1924 [see *Institution Notes*, No. 39, page (17), July 1923].

The resolution was seconded by **Mr. Roger T. Smith** and, after being put to the meeting, was unanimously adopted.

**Sir James Devonshire, K.B.E.** (Hon. Treasurer), moved the following Resolution : "That the Statement of Accounts and the Balance Sheet for the year ended 31st December, 1922,* as presented, be received and adopted." In doing so, Sir James Devonshire said : It is now my duty to submit the Statement of Accounts for the past year. Turning first to income and expenditure, it will be seen by the printed Report which has been issued to members that there is a surplus on the Revenue Account for 1922 of £862 2s. 8d. after making the provision of £3 000 for the Reserve Fund. This amount, which has been carried to the General Fund, compares with £639 2s. 10d. in 1921 and shows an increase of £222 19s. 10d., but it should be pointed out that last year £4 000 was put to Reserve, as against £3 000 for the year 1922. The total expenditure for 1922 is £32 084 15s. 2d. after taking credit for the amount of rents from tenants, which has hitherto been shown on the Revenue side, but on this, as well as on the last occasion, has been subtracted from the Expenditure side of the Accounts. This figure of £32 084 15s. 2d. compares with £29 921 14s. 9d. in 1921 and shows an increase of £2 163 0s. 5d. The principal items of this increase occur under the heads of "Management," which is up by £1 186, "Institution Building," £695, "Science Abstracts," £107, and "Local Centres," £364. There are also items appearing under the headings of "Commemoration Meetings," "Unveiling and Dedication of War Memorial" and "Faraday Medal," together amounting to £418, which substantially will not recur. On the other hand, there are savings under several heads, namely, "Journal," £332, "Special Grants and Research," £57, "Annual Dinner," £43, "Conversazione," £60, and "Mortgage Interest," £252. This last reduction of £252 is mainly due to the voluntary repayment of £3 000 to the Economic Life Assurance Society in 1922. Already for this year we have made a further payment to the Economic Life Assurance Society, which I am glad to tell you has now wholly discharged the outstanding mortgage on the Tothill-street property. On the credit side of the Account the Income shows an improvement of £471 4s. 1d. (after making the adjustment in regard to the rents from tenants). This improvement is mainly due to subscriptions, which brought in an extra £2 837, this amount being offset, however, by a decrease of £562 in the entrance fees received during the year. A small amount of £94 8s. 3d. was received for Life Compositions, as against nothing received under this head for 1921. The decrease in the rents from tenants amounts to £2 375, viz. £2 491 8s. 0d. as against £4 866 8s. 0d. in 1921, due to the termination of the occupation by the London County Council of the second and third floors of the Institution building at the end of the June quarter of 1922. I am glad to be able to state, however, that since the close of our accounts for the year 1922 we have let most of these rooms. The rents from the Tothill-street property show an increase of £121 owing to the fact that the increased rentals paid by some of the tenants appear in full for the first time. Turning now to the Balance Sheet, the first item is "Economic Life Assurance Society," which last year stood at £24 331 19s. 11d. and was reduced in 1922 to £20 338 6s. 5d. by £3 993 13s. 6d. made up of two items, viz. the amount of the obligatory repayment to the Society, and the voluntary repayment, to which I have previously referred, of £3 000 from the Reserve Fund. As a consequence of this substantial reduction of the mortgage, the interest payable is now materially reduced. The Reserve Fund (Contingencies and Mortgage Redemption) was increased by a transfer of £3 000 from the Income and Expenditure Account, and reduced by the amount of the voluntary repayment of £3 000, the total being £14 000 as in 1921. The General Fund now stands at £99 750 9s. 1d. as compared with £88 700 4s. 11d. on 31st December, 1921. There being no obligation on the part of the Institution, under the new Bye-Laws, to invest Life Compositions separately, the amount of the Life Compositions Fund, £5 590 10s. 0d., together with the amount of £94 8s. 3d. received during 1922, has been transferred to the General Fund and the investments have been added to those of the General and Reserve Funds. On the Assets side the value of the Institution Building and Lease is shown as £69 012 12s. 2d. as against £69 371 14s. 2d. in 1921, a difference of £359 2s. 0d. This difference is accounted for by the Surrender Values of the Sinking Fund policies, which each year show an increasing amount over the £277 12s. 2d. paid in respect of the policies. As members are aware, these policies have been taken out in order to secure the principal sum of £75 000 at the termination of the lease of the Institution Building in 1984. The statement in the Council's Report (see page 601) relating to the surplus of Assets over Liabilities is shown in the amended form adopted for the first time in the 1920 Accounts, in which the values of the actual properties shown on the Assets side, less the Liabilities, are given in full. These figures reveal that this surplus is now £114 399 2s. 1d., an improvement over 1921 of £5 459 14s. 2d. In conclusion, I think the Institution has every reason to be gratified with its financial position as disclosed by the Accounts, which I now submit for their adoption, and I formally move "That the Statement of Accounts and the Balance Sheet for the year ended 31st December, 1922, as presented, be received and adopted."

---

* See page 604.

The Resolution was seconded by **Captain R. J. Wallis-Jones** and, after the Honorary Treasurer had replied to comments by **Mr. F. W. Purse,** was unanimously adopted.

The following Resolution moved by **Mr. Ll. B. Atkinson** and seconded by **Mr. W. M. Selvey,** was carried with acclamation: "That the best thanks of the Institution be accorded to the following officers for their valuable services during the past year: (*a*) The Honorary Secretaries of the Local Centres and the Local Honorary Secretaries and Treasurers abroad; (*b*) The Honorary Treasurer (Sir James Devonshire)."

**The President** then moved "That Messrs. Allen, Attfield & Co. be appointed auditors for the year 1923–24." The resolution was seconded by **Mr. W. R. Cooper** and carried unanimously.

After the **President** had announced the premiums awarded by the Council for the year 1922–23 [see *Institution Notes*, No. 39, page (17), July, 1923], the meeting terminated at 7.25 p.m.

## 31st MEETING OF THE WIRELESS SECTION, 6 JUNE, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. E. H. Shaughnessy, O.B.E.,** took the chair at 6 p.m. in the unavoidable absence of the Chairman of the Section. The minutes of the meeting of the Wireless Section held on the 2nd May, 1923, were taken as read and were confirmed and signed.

**The Chairman** reported that no further nominations having been received for the Wireless Section Committee, the Committee's nominees had been duly elected. He also announced the premiums awarded by the Council for papers read before the Wireless Section during the Session 1922–23 [see *Institution Notes*, No. 39, page (18), July 1923].

A paper by Mr. C. E. Horton, entitled "Wireless Direction-Finding in Steel Ships" (see page 1049), was read and discussed and the meeting terminated at 7.50 p.m.

## SPECIAL GENERAL MEETING OF CORPORATE MEMBERS AND ASSOCIATES OF THE INSTITUTION OF ELECTRICAL ENGINEERS (INCORPORATED UNDER THE COMPANIES ACTS 1862 AND 1867), 19 JULY, 1923.

(Held in the Institution Lecture Theatre.)

**Mr. F. Gill, O.B.E.,** President, took the chair at 5 p.m.

The Notice convening the meeting was taken as read.

**Sir James Devonshire, K.B.E.,** as one of the liquidators, stated that all the liabilities of the old Institution had been discharged and its property transferred to the new body and moved "That the Report and Accounts of the liquidators be adopted."

The Resolution was seconded by **Mr. J. S. Highfield** and, after being put to the meeting, was carried unanimously.

The following Extraordinary Resolution, proposed by **Mr. Ll. B. Atkinson** and seconded by **Dr. A. Russell,** was carried unanimously: "That the Liquidators be and are hereby instructed to hand over the books, accounts and documents of the Institution of Electrical Engineers, incorporated under the Companies Acts 1862–1867, and of the Liquidators thereof, to the Institution of Electrical Engineers, Incorporated by Royal Charter, 1921."

**Mr. Ll. B. Atkinson,** after referring to the difficulties encountered in effecting the liquidation, moved that a hearty vote of thanks be accorded to the two liquidators, Sir James Devonshire and Mr. Rowell.

The resolution was seconded by **Mr. J. S. Highfield** and, after being put to the meeting, was carried with acclamation. **Sir James Devonshire** briefly replied and the meeting terminated at 5.20 p.m.

# OBITUARY NOTICES.

HERTHA AYRTON (*née* Phœbe Sarah Marks), the first lady member of the Institution, passed away after a short illness on the 26th August, 1923, at the New Cottage, North Lancing. Born at Portsea of Jewish parents, Miss Marks was educated in London by her aunt, Mrs. Hartog, and at the age of 16 began to earn her own living by teaching. After some years of this work she went to Girton where she made a special study of mathematics and gained Third Class Honours in the Cambridge Tripos. Whilst at Girton Miss Marks gave early evidence of ingenuity and originality, for during her college course she invented and constructed a sphygmograph for recording pulse-beats, and on her return to London patented a line-divider whereby any line could be divided into any given number of equal parts. In 1884 Miss Marks entered the Finsbury Technical College as a special student, and in the following year became the wife of the late Prof. W. E. Ayrton, Professor of Applied Physics in the Central Institution of the City and Guilds of London Institute, now the City and Guilds (Engineering) College, South Kensington. Interest in matters electrical had been aroused during her studentship at Finsbury, and afterwards Mrs. Ayrton was naturally concerned in the many researches being pursued by her energetic and versatile husband. In the early nineties a lengthy and arduous investigation on the electric arc was being carried out by Professor Ayrton and his students, and the intricacy and variability of the results led Mrs. Ayrton to study the phenomena and continue the research during the professor's absence in America. This she did with conspicuous success, and unravelled many of the puzzling peculiarities the arc presented. The results of her work and that of her husband were given in a series of articles in the *Electrician* during 1895 and 1896 and in papers before the British Association 1895, 1897 and 1898. The *Electrician* articles contained a summary of previous work on the subject, and, together with her further researches, were amplified and published in book form in 1902. The book still remains a standard work on the arc.

Mrs. Ayrton read a memorable paper on the "Hissing of the Electric Arc" before the Institution in 1899, for which she was awarded a Premium, and in the same year she was elected a Member. A paper on "The Light of the Arc," before the International Congress of Electricity at Paris in 1900, was made the subject of a special vote of thanks by the section of the Congress in which it was read. Another important paper on "The Mechanism of the Electric Arc" was read before the Royal Society in 1901 and published in the *Philosophical Transactions* of that Society. In 1906 the Council of the Royal Society awarded Mrs. Ayrton the Hughes Medal. Her work on the arc naturally directed Mrs. Ayrton's attention to the properties of various kinds of carbons used in arc lamps, particularly those for searchlights and cinema and film studio lamps. For such purposes the candle-power per watt, regularity and steadiness of burning and the effective life of the carbons are matters of great importance, so she began a lengthy research to find the best sizes, materials and proportions for heavy-current work. Scores of carbons of different kinds were designed, made and tested early in the last decade, and six patents for carbons and carbon holders were taken out in 1913 and 1914. Some of the improvements there described are now in common use.

As an artist Mrs. Ayrton possessed no mean powers, and her gifts in this direction enabled her to make excellent large-scale coloured drawings of the arc under various conditions ; it is to be hoped that these drawings may be preserved in the archives of the Institution. Other subjects in which Mrs. Ayrton was interested and which she studied with great success were the "Motion of Oscillating Water" and the "Origin and Growth of Sand Ripples." Papers dealing with these phenomena were read before the Royal Society, and lectures and demonstrations on the phenomena were given at Royal Society soirées and elsewhere.

Shortly after the first gas attack by the Germans in 1915 Mrs. Ayrton brought her knowledge of fluid motion to bear on the problem of protecting our troops from the dangers involved, and as the result of much experimental work devised the "Ayrton flapper fan" for driving off poisonous gases. After much official inertia had been overcome, about 100 000 of these fans were made and supplied to our troops in France and Flanders. The invention, the development of which involved considerable expense, was presented gratis to the nation. During 1918, motor-driven flapper fans were made and used experimentally for clearing dug-outs, trenches, etc., from poisonous gases. After the armistice Mrs. Ayrton applied her invention to the propulsion of gases and liquids through pipes, the aim being to improve the ventilation of mines, underground tubes and sewers. She was engaged in this work until a few weeks before her death.

Marked characteristics of Mrs. Ayrton were the skill and patience she displayed in carrying out difficult and tedious experimental work, and the remarkable insight into natural phenomena which she possessed. Socially she was large-minded, generous and kind-hearted, and her own description of her benefactress, Madame Bodichon, viz. "Her great intellect and noble presence were an inspiration to all who knew her," is particularly applicable to herself. T. M.

EDWARD FUHRMANN CLARKE, who died on the 19th February, 1922, was born on the 17th November, 1857, and received his education at Shrewsbury School. After serving his apprenticeship from 1873 to 1876 with the North-Eastern Railway Co., he obtained an appointment on the New Zealand Government Railways, later being placed in charge of the installation of their new locomotive works at Petone. In 1882 be joined the Wellington Woollen Manufacturing Co., Ltd., of New Zealand, and was responsible for the erection of their buildings, plant and machinery, including a complete electric lighting installation. In 1886 he had charge of the installation of the electric lighting plant for the New Zealand Government printing works, and afterwards took up consulting work in Wellington. In 1889 he returned to England and engaged in experimental work in connection with refrigerating machinery, and in 1893 commenced practice in Birmingham as a consulting engineer. He was appointed consulting engineer to the North of Ireland Shipbuilding Co., Ltd., in 1914, and in 1915 was appointed in a similar capacity to the Sutton Coldfield Electricity Works. He was elected a Member of the Institution in 1918.

JOHN CHARLES HOMFRAY DARBY was born on the 28th July, 1864, and received his early education at Twyford, near Winchester. From there he went to Charterhouse, where he remained until 1881. He entered the service of the Eastern Extension Australasia and China Telegraph Company, Ltd., in April 1883, as a telegraph operator, in which capacity he served at Cape St. James (Indo-China), Haiphong (Tonquin), Shanghai and Foochow. Having early shown a marked electrical ability, he was promoted in 1887 to the position of assistant electrician on the staff of the company's cable-repairing steamers stationed at Singapore, later becoming electrician in charge of a cable steamer. In July 1909 he became assistant manager of the company's cable factory at Singapore, to the managership of which he was appointed two years later. He held this position until he retired from the service in June 1921. To his energy, resource, fitness and conscientious work are largely due the very successful results obtained at the factory, at which the supply of cable necessary for repairs of the company's system was steadily maintained throughout the war. With the late Mr. H. K. C. Fisher he edited a very valuable book entitled "Students' Guide to Submarine Cable Testing," which has proved a very great help to telegraphists all over the world, and which has been adopted as one of the textbooks in the syllabus for staff examinations of many cable companies. He was also an artist and many of his paintings of scenes and life in the Far East have been shown at art exhibitions in Australia and Singapore. His pleasing personality and his readiness to help others endeared him to all his colleagues, by whom his departure from active service in the East was much regretted, and his decease, so soon after his retirement, on the 21st August, 1922, was deeply lamented. He was elected an Associate of the Institution in 1883 and a Member in 1913. R. T. W.

ARTHUR LOVEL DEARLOVE was born at Higham Park, Northamptonshire, on the 10th April, 1859. He was educated at Salway House, Leyton, and afterwards by private tuition, subsequently going to King's College. He received his mechanical training with the firm of Latimer Clark, Muirhead and Co., with whom he remained for three years, during the latter part of which period he was employed in the laboratory. After being engaged in the establishment of duplex working between London and Emden in 1878, he joined the firm of Messrs. Clark, Forde and Taylor, submarine cable engineers. In 1888 he took part in the laying of the cables between Venezuela, Curaçao, San Domingo, Haiti and Cuba by Messrs. Henley's Telegraph Works Co., and in 1897 he was for some months engaged in cable-repairing and cable-laying operations carried out by the Compagnie Française des Cables Télégraphiques. In the following year he became a partner in the firm of Alfred Graham and Co., electrical and telephone engineers, and in the same year he was admitted a partner in the firm of Clark, Forde and Taylor, with whom he remained until his death, which occurred on the 19th October, 1923. He was elected an Associate of the Institution in 1897 and a Member in 1898.

SIR JAMES DEWAR, M.A., F.R.S., was born at Kincardine-on-Forth on the 20th September, 1842. After being educated at Dollar Academy he went to Edinburgh University, where he was a pupil of, and later became assistant to, Lord Playfair, who was at that time Professor of Chemistry. In 1875 he was appointed Jacksonian Professor of Natural Experimental Philosophy at Cambridge. Two years later, in 1877, he became Fullerian Professor of Chemistry at the Royal Institution and retained that position until his death, which occurred on the 27th March, 1923. His important researches on the liquefaction of gases and the properties of matter at temperatures approaching absolute zero were carried out at that Institution. By 1886 he had produced oxygen in the solid state, and by 1891 he was making liquid air in large quantities. In the following year he invented the vacuum container in which liquid air could be stored. In 1898 he succeeded in liquefying hydrogen, and in the following year obtained this gas in the solid state. He also attacked the problem of the liquefaction of helium, but was prevented by ill-health from carrying out his purpose. In addition to investigating the physical constants of the liquefied gases, he also conducted researches on the electrical resistance and thermo-electric, magnetic and dielectric constants of various substances at low temperatures. In much of this work he acted in conjunction with Prof. J. A. Fleming. His research on the properties of radium at low temperatures also added much to our knowledge on the subject of radioactivity. In other branches of science his researches include the physiological effect of light, spectroscopic investigations, the diffusion of gases, and the properties of thin liquid films, while in 1888, as a member of the Explosives Committee, he invented, in conjunction with Sir Frederick Abel, the smokeless powder known as cordite. He was elected a Fellow of the Royal Society in 1877, and a Member of the Institution of Electrical Engineers in 1881. In 1904 he received the honour of Knighthood.

JAMES FRASER, who retired from the position of Post Office Engineer at Aberdeen only a short time prior to his death, joined the Post Office in Aberdeen in 1877, and after service as a telegraphist was transferred to the engineering department and appointed relay clerk at Nevin. He was promoted to be a second-class engineer in the Central Metropolitan District and transferred later to the Designs Section at Headquarters. He was then promoted to the rank of executive engineer at Sunderland, but returned to London as engineer in charge of the C.T.O. Section, and later returned to the Telegraph Section of the Engineer-in-Chief's office. In 1918 he was transferred to his native town, where he continued to reside after his retirement. As a teacher of magnetism and electricity and telegraphy he was most successful. Himself a triple medallist of the City and Guilds, he inspired his students with the fire of his own zeal, and his classes at the Northampton Institute were attended by large numbers of the C.T.O. staff. In 1910 he was awarded the Junior Silver Medal of the Institution of Post Office Electrical Engineers for his paper on "The Theory and Development of Common Battery Telegraphs," and in the October 1917 issue of the *Journal* of that Institution he contributed a valuable article on the duplex balance, which investigated mathematically the conditions necessary to secure a balance on long high-capacity lines on both differential and bridge systems of duplex. He was chairman of the Aberdeen Sub-Centre of the Institution 1921–22, and when he withdrew from active teaching work he was appointed examiner in magnetism and electricity for the City and Guilds of London Institute, a position he held until his death, which occurred on the 4th October, 1922. In September 1914 he was sent to France to supervise the termination of a cross-Channel cable, and for his services he was awarded the 1914 medal, being the only civilian, it is believed, to receive that honour. He was held in the highest regard by his colleagues, revered by his pupils and esteemed as a man of sterling worth. He was elected an Associate of the Institution in 1886, an Associate Member in 1909, and a Member in 1922. W. N.

SIR JOHN GAVEY, Past-President, died on the 1st January, 1923, in his eighty-first year, having been born on the 11th August, 1842, at Jersey, where he was educated at the Victoria College.

His active professional career commenced in 1861 when he entered the service of the Electric and International Telegraph Co., and his experience of 10 years in the development of the telegraphic business under private enterprise was always highly valued by him. On the acquisition of the telegraphs by the State in 1870 Sir John became a civil servant, receiving the appointment of Superintendent of the South-Eastern division of telegraphs and subsequently of the Great Western sub-division of the Southern division of England with headquarters at Bristol. In 1878 he removed to Cardiff, having been appointed Superintendent Engineer of the South Wales district. He was transferred to London in 1892 on his appointment as Chief Technical Officer at headquarters. Promotion to Second Assistant Engineer-in-Chief followed in 1897; to Assistant Engineer-in-Chief and Electrician in 1898; and to the highest post in the Department, Engineer-in-Chief, in 1902, which office he held until 1907, when he retired under the age limit, but was appointed as a Consulting Engineer to the Department in the following year. On his retirement from Government service he acted as Consulting Engineer of the Monte Video Telephone Co. and became a Director of the United River Plate Telephone Co. and subsequently President. This office he resigned through failing health, but remained a Director, which appointment he retained until his death.

Sir John joined the Institution as an Associate in 1872, the year after its foundation as the Society of Telegraph Engineers, and became a Member in 1877. He was elected to the Council in 1899, became Vice-President in 1900, and President in 1905. He was elected a Member of the Institution of Civil Engineers in 1899. He was created C.B. in 1902 and received the honour of Knighthood in 1907. Of fine stature and good physique, Sir John was the picture of health and strength and it was a surprise and shock to his friends to learn a year or two before his death of his being stricken with illness from which recovery was not to be expected and suffering was to be feared. Until this illness came upon him he remained active and alert in spite of the 60 years or more of strenuous work upon which he could look back. This work covered the technical and administrative features of wire telegraphy, experiments in wireless and the development of telephony. The span that he bridged was a wide one—from semaphore telegraphs to wireless speech; for, as he himself recalled on an interesting occasion, the last of the semaphore telegraphs, that working between Liverpool and Holyhead, was abandoned and the electric telegraph substituted in the same month of February 1861 as he commenced his professional career.

In 1874 he read a paper before the Institution on "Earth Boring for Telegraph Poles," in 1878 on "Insulators for Aerial Telegraph Lines," in 1896 on "The Telephone Trunk Line System in Great Britain" and in 1900 on "Telegraphs and Telephones at the Paris Exhibition," as well as his presidential address in 1905 devoted appropriately to telegraphic and telephonic subjects.

But his contributions on technical subjects were not limited to the Institution. As early as 1873 he was writing to the *Telegraphic Journal and Electrical Review* explaining an alleged "discovery in the science of electricity," and in 1875 contributed to the same journal a series of articles "On Telegraph Construction" which had a characteristically practical purpose, the object laid down in the prefatory lines being the endeavour "to deal with the subject in a sufficiently elementary manner to enable those members of the telegraph staff who have little or no outdoor experience to lay the foundation of that knowledge which they may be called upon to apply practically at a later date." In 1887 he read a paper before a Cardiff scientific society "On Some Investigations in Electrical Induction," which recorded the success attending the Porthcawl experiment in wireless telegraphy. Before the same society he read a paper in 1890 on "Recent Advances in Electricity and its Appliances," and in

1910 delivered the James Forrest lecture at the Institution of Civil Engineers, choosing for his subject an account of the "Recent Developments in Telegraphy and Telephony." Though telegraphy covered a longer period it is his work in telephony that looms largest outside the Department. Of the numerous early telephonic enterprises of the Government two survived, Newcastle and Cardiff, and for many years Sir John was stationed at Cardiff.

The system was a small one and the telephonic activities of the Department as a whole could not provide the experience needed for embarking on a great scheme. Sir John was marked out as the man to be in charge of the telephones. He was selected to value, on behalf of the Post Office, the trunk lines purchased from the National Telephone Co. in 1895, and, when it was contemplated that the Government should undertake telephone work on a large scale, Sir John made a study of the problems involved in America and Europe. He visited the United States in 1898 and in 1905, investigating thoroughly the technical and commercial features. The design and construction of the London telephone system of the Post Office was carried out under Sir John's supervision. It was a great work well done, but his services to the State in this connection are not limited to the engineering side. It will be recalled that public clamour called for a Post Office competition, whilst the Government eventually decided upon co-operation with the existing companies. It is safe to assume that Sir John's investigations had satisfied him of the undesirability of competition and the superior benefit to the State of a co-operation leading to the general absorption on the expiry of the National Telephone Co.'s licence. It was in some quarters a very unpopular decision, but it was very prudent, and it is without doubt that to Sir John's sound judgment the ultimate policy was largely due. His knowledge of French is doubtless to be ascribed to his Channel Island birth and training, but this knowledge was of great advantage to the Department and to the companies with which Sir John was subsequently connected. He was a Juror in the Electrical Section of the Paris Exhibition in 1900, and a delegate to the International Electrical Congress in the same year. In 1903 he represented the Post Office at the International Congress on Wireless Telegraphy held in Berlin, as also at the Wireless Convention held there in 1906. He paid three visits to Argentina as a Director of the United River Plate Telephone Co., and the advantage to the Institution of his knowledge of French was made evident more especially in connection with the visit of kindred Institutions during his Presidency.

Sir John was a man of simple tastes and even temper, though capable of administering a severe rebuke to a subordinate who deserved it, and always ready to stand up to his superiors with an intelligent loyalty for the Department which he controlled. He was a man upon whom responsibility did not sit lightly, but it was carried with equanimity when he had examined his problems and was satisfied as to their solution. Self-seeking in any form was contrary to his nature, and he took what seemed almost meticulous care to ascribe to a section or individual in the Department or outside any credit which might be their due in connection with the subject with which he might be dealing. Those in close touch with him regarded him with affection based upon respect. J. E. K.

HOWARD CLARK HEAD after being educated at the Philological School, Marylebone, was apprenticed to Messrs. Watson and Sons, manufacturers of scientific instruments. He organized the X-ray and electro-medical department of that firm and opened workshops for the manufacture of induction coils, switchgear and wireless apparatus. From 1902 to 1903 he was manager of the electrical department of R. W. Paul, and from 1903 to 1907 he had charge of the X-ray and electro-medical department of Messrs. Isenthal and Co. He then took up a position with Messrs. Siemens Bros. and Co., where he started their X-ray and electro-medical department. While with this firm he introduced the high-tension transformer plants which superseded the induction coil, and was concerned in the manufacture of single-flash transformers, electro-cardiographs and continuous temperature recorders. From 1914 to 1919 he devoted his whole attention to designing and manufacturing apparatus for war purposes, amongst other things being mobile X-ray wagon units. He later joined the board of Messrs. Watson and Sons (Electro-Medical), Ltd., a company into which the X-ray department of Messrs. Watson and Sons had developed. He died at King's College Hospital on the 7th February, 1923, having been in indifferent health for several years. He was elected a Member of the Institution in 1921.

ARTHUR WEST HEAVISIDE, I.S.O., who was born on the 30th June, 1844, was one of the early members of the Institution, having been elected a Member in 1877.

With the passing of "A.W.H." the last of the old pre-Post Office Telegraphs veterans has gone; but at a ripe old age, surviving many of the next generation of Post Office district chiefs. So far as history goes back, his first association with telegraphy was in the Universal Private Telegraph Co., which he joined at Newcastle on the 1st January, 1861. At the transfer he was District Superintendent; but his later record shows that he must have had other experience, and tradition has it that he was trained by his uncle, Sir Charles Wheatstone. At the transfer of the telegraphs to the Post Office in January 1870 he was placed in charge of the North-East (North) District with headquarters at Newcastle, from which he retired on the 1st September, 1904, so that throughout his career he was stationed at one place.

From the first he appears to have been an enthusiastic experimenter. Amongst the Engineering Department records there is a drawing which shows a row of about 20 A.B.C. indicators ranged above a peg-switch with bars crossing horizontally and vertically, and an A.B.C. communicator. It is probably dated 1880—the writer's first year in the Post Office—and represents the Newcastle private-wire switch by which the city merchants were enabled to intercommunicate. How long it had taken Heaviside to build up the system before the need for a larger "Umschalter switch" forced him to "confess," and what sort of a "row" there was when he did confess, the writer was too young to be permitted to know! but he ventures to think that that device was the precursor of the telephone exchange. Indeed, it is not unreasonable to hold that the existence of the private-wire Wheatstone A.B.C. system was actually a factor in retarding the development of the telephone in this country. The telephone then was not what the telephone is now, and the expert A.B.C. operators could do wonders in speed on their instruments. Heaviside went among the Newcastle merchants and manufacturers, taking note of what would be most likely to meet (or create) their needs. Later on he began systematically to convert his "switch" to a "telephone exchange," and therein developed all sorts of "gadgets." How he enjoyed the fights with Headquarters about them! How often when he was foiled by higher authority he consoled himself with the thought that "all things will come to him that will wait"—and later on saw to it that they came! His system provided secrecy, so that no third party, not even the operator, could be in circuit once two people were put through. To the writer was assigned the task of designing the first multiple switch in England and it had to meet this requirement for Newcastle. Then Heaviside was pioneer of underground wires for telephones, so that open wires practically did not exist for telephone subscribers at Newcastle from very early days.

He had a wider outlook, however, and was one of the most active of the founders of the Newcastle Electricity Supply Co. and acted as their consulting engineer. Also he was the first Chairman of the Newcastle Local Section (now North-Eastern Centre) of the Institution in 1900–01. In 1881 he presented a paper to the Institution on induction between telegraph and telephone wires. On the moors of Northumberland he supervised all Preece's earlier investigations of inductive wireless telegraphy. In fact, wherever there was a chance of getting in touch with the latest developments of electrical science or of getting in front of them Heaviside jumped at it.

He had robust health and was fond of outdoor life. He assisted in the formation of the Tyneside Volunteer Submarine Engineers; and one may assume that he was one of their most active members. He was held in universal esteem and respect by every member of his staff, as a keen, just business man and a gentleman.

After his retirement he contributed a paper to the Institution of Post Office Electrical Engineers, and he was recalled to the Post Office for about a year to assist on the Post Office valuation staff of the National Telephone Co.'s system. After that only a few of his old colleagues kept in touch with him. During the war he went to Torquay, and this year he returned to London apparently still his old self but somewhat feeble. He passed away on the 22nd September, 1923. A. J. S.

HERBERT WOODVILLE MILLER received his technical training at King's College, London, and later went to Cromptons as a pupil at a time when electrical distribution was in its infancy. He showed so much originality and talent that, towards the end of his pupilage, he was employed in Colonel Crompton's laboratory as his personal assistant, being responsible for much of the early experimental work on the Planté accumulators which were then being adopted to store electric energy for small installations, and for lighting private houses in town and country. When Crompton started the first house-to-house electric supply from Kensington Court in 1886, he put Mr. Miller in charge of it, the first supply station, and he became successively assistant engineer, engineer-in-chief and managing director of the Kensington Company. He served the company throughout the whole of his career, a period of 36 years, up to the time of his death. It was due to his uninterrupted, true and faithful service, and to his intelligent use of his plant, that his company rose to a position of steady prosperity. When the demand on interurban supply stations became so great that the supply had to be supplemented from external generating stations, where the supply is generated and thence transmitted at high pressure to the original interurban stations which then become mere distributing centres, Mr. Miller worked out his system independently, and the generating station designed by him in 1900 situated at Wood Lane, which supplied his own and another company, has throughout been a model of what such stations should be, combining economical use of capital with high efficiency of production. During recent years, his work has shown extremely economical results and given great satisfaction to users. He obtained his results by judgment in the selection of his assistants, and by succeeding in securing the goodwill of those under him. He paid close attention to a subject which at first had been too little considered, i.e. the improvement of the methods of generating steam by the hand-firing of boilers, by substituting the self-acting under-grate stokers known by his name. So closely was his name connected with the direct-current supply coupled with accumulators that he became a leading authority on this system and was much consulted. His death leaves vacant a place that will not be readily filled. During the long and painful illness which preceded his death on the 4th December, 1922, he never lost touch with his duties, and only those who were co-workers with him, of whom the writer was one, are in a position to appreciate his heroism and devotion to duty almost up to the day of his death. He was elected an Associate of the Institution in 1890, and a Member in 1899, and was a Member of Council from 1896 to 1898. R. E. C.

HERBERT EDWARD MITCHELL received his technical education at the City and Guilds Technical College, Finsbury, from 1883 to 1885. He was subsequently engaged on electric lighting contracts for various firms until 1888. From 1888 to 1898 he was chief assistant to Prof. George Forbes in connection with the latter's consulting work, including the scheme put into operation for the electrical transmission of power from the Niagara Falls, and he was one of Prof. Forbes's staff of engineers who in the winter 1897–8 spent some months in Egypt investigating the possibility of utilizing and transmitting electrical energy from the Nile cataracts. After 1898 he was engaged on various electric lighting undertakings in London and the provinces, and while in private practice in later years he prepared the original scheme for the heating and ventilating of the new County Hall, Westminster. During the last five years of his life he held an appointment as civil engineer in the Air Ministry, and in that capacity designed the heating and ventilating equipment of the Royal Air Force Depot at Halton, one of the largest works of the kind ever carried out. He also designed the electrical installations at various aerodromes for the Air Ministry. He died on the 23rd July, 1923. He was elected an Associate of the Institution in 1888 and a Member in 1898.

MARK HEATON ROBINSON, who died on the 2nd February, 1923, was born in 1844, the son of Commander Edward Robinson, R.N., and was educated at the Royal Naval College, New Cross. As a young man he entered the Admiralty, where he served for 13 years. In 1880 he entered into partnership with the late Mr. Peter Willans and they were successful in producing a high-speed engine suitable for launches, etc., and established a small works at Thames Ditton. About this time Robinson improved the high-speed engine by employing an independent air buffer for correctly cushioning the reciprocating piston independently of the load, and shortly afterwards Willans designed the celebrated central-valve high-speed engine, which was at once adopted by Crompton and others for direct coupling to dynamo-electric machines, for which purpose it was a brilliant success. A very large business rapidly developed. The construction of this engine required a degree of accuracy and interchangeability which at that time was not being achieved in any engineering works in this country, and Willans and Mark Robinson threw themselves whole-heartedly into the new problem of production on a commercial scale, with what were then considered to be extraordinary fine limits of accuracy. The works at Thames Ditton became an object lesson and the centre of ceaseless visits of engineers, where the new procedure, with tool rooms nearly as large as the works in the first instance, was a revelation to the then engineering experts. Willans's sudden and untimely death, whilst it was a tremendous loss to the engineering world, did not stop the success or progress of this remarkable business, and in the year 1897 new works on a large scale were planned and built at Rugby, Mark Robinson, who was then chairman of the company, taking the leading part in this great expansion. The check to the prosperity, and the vicissitudes, financial and other, that fell upon the business, need not here be recounted, but there is no doubt that they were an immense strain on Mark Robinson's health, and in the year 1909 he retired from active participation in the work of the company. In later years he was occupied in London in work with the Kent coal field, and more particularly with Sandwich Haven, afterwards known as Richborough Port. The designs for this port were practically identical with those he originally put on paper. He was a well-known figure in engineering circles and engineering gatherings until a few months ago. He was elected a Member of the Institution in 1888, and served on the Council from 1901 to 1903. In 1895 he read a paper before the Institution on " Recent Development of the Single-Acting High-Speed Engine for Central-Station Work," for which paper he was awarded the Institution Premium in 1895 and the Willans Premium two years later. He married in 1864 and had eight sons and eight daughters.

L. B. A.

SIDNEY SHARP was born in 1850 at Albury, Surrey, and died at Ealing on the 1st March, 1923. He was a son of Mr. Samuel Sharp of Tangleymere and was educated at Henley-on-Thames under Dr. Godby. Early in his business career he went to South Africa, where for a time he was in a business firm in Port Elizabeth. In 1870, in the great rush to the diamond fields, Mr. Sharp went up country with some friends, but not long afterwards returned to England to assist his father in the business of S. Sharp and Sons, Chilworth, Surrey, manufacturers of gunpowder. In 1881 this business was voluntarily terminated, and Mr. Sidney Sharp decided to devote himself to electricity, which was just beginning to take its place in the engineering world. One of the earliest undertakings of which he had charge was the lighting of the Oldham Exhibition in 1884, subsequently being responsible for the installation of electric lighting plant at Ashton Court, Bristol. In 1886 he entered into partnership with Mr. J. M. V. Money-Kent, and the firm of Sharp and Kent, in a practice lasting over some years, was responsible for electric generating stations, etc., at Holloway, Guildford, Kelvinside, etc., as well as the first plant in the Houses of Parliament. The partnership being dissolved and the Kelvinside station having been taken over by the Glasgow Corporation, Mr. Sharp returned in 1898 from that city, where he had resided for some time, to London, taking up his residence in Ealing and continuing a consulting practice in Victoria-street, Westminster, where he became well known. His work was mainly concerned with the installation of lighting and other plant in large institutions, etc., and in this direction he was responsible for installations at Netherne County Asylum, Park Prevett County Asylum, Maynooth College, Hardwicke Grange (for the late Mr. Frank Bibby) and Rossie Priory (the late Lord Kinnaird), etc. He was for long an active member of the Institution, having joined in 1886 as an Associate, and becoming a Member in 1891. He served on the Council in 1890. He was also one of the Honorary Auditors, and did much valuable work and devoted a great deal of time to the affairs of the Institution, on the occasion of a vacancy in the secretaryship, which lasted for some time. He was also a Member of the Institution of Mechanical Engineers, and Honorary Secretary of the Dynamicables, a circle in which the genuine and genial traits of his character were much appreciated. He retired from business in September 1922 owing to his health, which he felt latterly was at times not equal to the demands of the work in which he was accustomed to engage.

E. M. C.

ALFRED INIGO SUCKLING-BARON was born at Hungerford on the 16th August, 1863, and died on the 20th March, 1922. He was the youngest son of the

Rev. W. J. Baron. Brought up principally in the country, he developed a love for fishing at a very early age and proved always fond of games and sport in general. At the age of nine he was sent to St. John's Foundation School for the Sons of the Clergy, at Leatherhead, remaining there until he was seventeen. A certain amount of business training, for which he always expressed his appreciation in after years, followed in the service of the London and County Bank. This work, however, made no appeal to him ; his great ambition lay more in the direction of engineering. Naturally, it was a great pleasure to him when, through the kindness of a relative, he was able to start serious training at the Hanover-square School of Electrical Engineering. After completing the course he joined the Gulcher Electric Light and Power Co., and in 1886 went on business to Wellington, New Zealand. He returned to England in January 1892, partly on business and partly on holiday, and went back to Wellington in the autumn of the same year to erect the new power house of that city. On his return from New Zealand in 1896 he joined the staff of the General Electric Co., as manager of their Manchester branch, which position he held for a year or two before he was called upon to form the Engineering Department in London in 1901. He remained at the head office until 1909, when the General Electric Co., with a view to creating a further outlet for their manufactures, decided to develop electrical power stations in different parts of the world. Their first venture was at Uitenhage in South Africa ; to this outpost Mr. Suckling-Baron was sent to make the necessary arrangements and plans for a generating station and distribution system. While in South Africa he obtained a further concession at Oudtshoorn. Both of these stations were designed and built to his own specifications, and very satisfactory business was the result of his efforts. He next entirely reorganized the power station and distribution system of the Madeira Electric Lighting Co. and succeeded in bringing order out of chaos. In 1913 he was sent to Frinton-on-Sea to report on the conditions existing at the power station there. He supervised the reconstruction of the whole system and during the same year obtained the Provisional Order for supplying electricity in Macclesfield, where he planned and carried out a complete system for the supply of electricity for power and lighting. The outstanding feature of all the work which he carried out was thoroughness in every detail, and the generating stations controlled by him rank amongst the most orderly and well kept in the country. He was undoubtedly an engineer of very high standing, and his death meant a great loss to the electrical industry. He was elected an Associate of the Institution in 1888 and a Member in 1892.

ADOLPH TOBLER was born in Zürich, Switzerland, on the 22nd July, 1850, and died in the same town on the 3rd July, 1923. His contributions to science were many and varied and as a writer of scientific articles he was very successful. As early as 1876 he was teaching in the University of Zürich as a private tutor. In 1889 he was made Honorary Professor and in 1905 lectured on "weak-current" engineering at the Eidgenossische Technische Hochschule, Zürich. In addition to the development of electric safety devices for railways, he also devoted much attention to telegraphy, telephony, cables and cable-testing, electric clocks and measuring instruments, his work being appreciated not only in Switzerland, but also in England and Germany. As a philanthropist he was also very well known, and the central library in Zürich owes its existence to his generosity. He was always willing to give a helping hand to the deserving. He provided many of the instruments in the Physics Department of the Zürich University, and at his home was to be found the most carefully equipped laboratory for measuring purposes. In spite of his financial position, he never attempted to obtain a controlling financial interest in the industry, as his sole ambition was the development of scientific research. His military career should also be mentioned. He started as a private in the field artillery and later joined the fortress troops on the St. Gothard. Here he advanced rapidly to the rank of Lieut.-Colonel and, as his experiences in cable work proved to be very useful, was given charge of the cable-laying in the construction of the St. Gothard fortress. On the outbreak of war in 1914, Professor Tobler, then 64 years of age, offered his services to the St. Gothard troops, and the country very gladly accepted them. Those who knew him will appreciate the loss which Switzerland, and especially Zürich, has suffered through his death. He was elected a Foreign Member of the Institution in 1877, and a Member in 1911.

FREDERICK THOMAS TROUTON was born in Dublin on the 24th November, 1863. He was educated at Dungannon Royal School and afterwards at Trinity College, Dublin, where he had the reputation of being a clever pupil, keen on scientific work. On taking his degree his work was further rewarded by the award to him of a large gold medal. Prof. G. F. FitzGerald was at that time Erasmus Smith Professor of Experimental Science. Trouton was one of his most distinguished pupils and later became his assistant and was thenceforward closely associated with his work. FitzGerald was one of the few who took seriously Clerk Maxwell's electromagnetic theory of light, and when Hertz and Lodge began publishing their experimental researches the Dublin laboratory at once became active. Trouton repeated and extended Hertz's experiments especially with a view to a determination of the direction of the vibrations of light (see *Nature*, vol. 39), and to an examination of the phases of secondary waves (see *Nature*, vol. 40). As a result, he was elected a Fellow of the Royal Society in 1897. Later on, again in response to FitzGerald's stimulus, he attacked a subject which has not yet passed out of the controversial stage, namely the relative motion of the earth and æther. "The fundamental idea of the experiment is that a charged electrical condenser, when moving through the æther, with its plates edgeways to the direction of motion, possesses a magnetic field between the plates in consequence of its motion in accordance with the generally held view that a moving charge is equivalent to an electric current." Trouton, after FitzGerald's death, further developed the investigation in connection successively with H. R. Noble and A. O. Rankine. In every case no effect indicative of relative motion was ever observed.

Trouton had meantime (in 1902) come to London as Quain Professor of Physics at University College. Together with his pupils he there carried out various researches, chiefly in connection with the general properties of matter. Subjects such as viscosity in solids and in quasi-solids like pitch and cobbler's wax engaged his attention. He devised various ingenious methods of tackling such problems. In the later active years of his life he made a very large number of measurements (many of which are still unpublished), conducted with the most scrupulous care, on the phenomena of absorption and adsorption ; for example, the adsorption of vapour by glass or by flannel, and still later adsorption from solutions by silica.

These experiments were being prosecuted when in 1912 he was seized by a serious illness from which he never recovered. He lived in a state of partial paralysis, though retaining his mental faculties, until the 21st September, 1922, when he passed painlessly away at the age of 58 years at his house at Downe in Kent.

As a scientific man Trouton was characterized, not by great knowledge, but by great instinct. He was a born experimentalist and had some amused contempt for the validity claimed for scientific theories. It must be remembered that the theories of physics had not yet gone into the melting-pot ; to-day his attitude would not have caused so much surprise. He is most widely known for a numerical relation in connection with molecular latent heats and discovered by him when a student, which is known universally as Trouton's law. Those who came into personal contact with him knew that they had to deal with a man of sterling integrity in all his dealings. He was of a kindly disposition. Although too serious intellectually to be regarded as gay, yet his conversation flashing with Irish wit and whimsicality could keep a room alive with laughter. He was fond of an outdoor life ; he delighted in gardening, cycling, tennis and golf, and took a great interest in the athletic life of University College. He married Annie, the daughter of George Fowler of Liverpool, who survives him. He lost two sons in the war : two sons and three daughters remain. He was elected a Member of the Institution in 1900. A. W. P.

ROBERT THORBURN TURNBULL was born in Wellington, New Zealand, in 1865 and was educated at Wellington College, Berkshire, England, and at Crystal Palace Engineering School. He became a pupil with Messrs. Woodhouse and Rawson in 1883 and commenced business as a partner in Thompson, Ritchie & Co. In 1891 he went out to Wellington, New Zealand, for the Gulcher Electric Light Co. and was in charge of the station plant for about 12 months. The firm of Turnbull and Jones, Ltd., electrical engineers and contractors, was formed in 1899, and he was connected with the firm until his death, which occurred as the result of a motor accident on the 12th July, 1923. He was elected a Member of the Institution in 1898.

JOHN WILLIAM ULLETT was born in 1859 at Higney Grange, Huntingdonshire, and was educated at the Merchant Taylors' School, London, and the School of Telegraphy, Hanover-square, W. His engineering career began in 1879 when he joined the Telephone Co., Ltd., London. He was thus closely associated with the telephone industry from the start and was responsible for the design of many of the earliest types of apparatus. Not a little credit is due to him for his pioneer work in this direction. He took a prominent part in designing the various systems of working the telephone service, notably in connection with the development in this country of the multiple switchboard, and devoted much time to original research. During the period 1889–93, when the majority of subscribers' lines were single wires with earth return, Mr. Ullett, associated with other engineers of the telephone companies, carried out a great deal of investigation work with the object of perfecting the design of a telephone transformer which could be used for the purpose of connecting these single lines to metallic circuit junctions and trunks. He also took an active part in the development of the differential transformer which made phantom working practicable and enabled the National Telephone Co. to adopt it on many junction and trunk lines. His energies, however, were not confined to the apparatus side only ; he was engaged in the early eighties in erecting junction lines in London, and a few years later the first trunk circuits between the metropolis and the north of England. In 1893 he planned and took charge of the National Telephone Co.'s factory at Nottingham, and in 1901, in order to cope with the largely increased demand, additional works were established under his direction at Beeston for the manufacture of new apparatus, only repair work remaining at the Nottingham factory. Both establishments were controlled by Mr. Ullett until 1903, when the British L.M. Ericsson Manufacturing Co., Ltd., took over the Beeston works. Mr. Ullett was then transferred to this company as works manager, which position he held until 1918, and under his management these works were considerably extended and improved. During the war Mr. Ullett was a member of the Advisory Committee which equipped and controlled the Nottingham National Shell Factory. His intimate knowledge of factory costings was of the greatest value and the factory soon became noted as one in which the production costs were kept extremely low. In 1919 Mr. Ullett was engaged by Mr. J. G. Small, ex-Mayor of Nottingham, as engineering adviser for several industrial concerns under the latter's control, and was appointed managing director of the Amos Tatham Needle Co., Ltd., Ilkeston ; under his charge this business was extended considerably overseas. He was also consulting engineer to the Jacoby Bleaching Co., Ltd., Daybrook, Nottingham. He was elected an Associate of the Institution in 1884 and became a Member in 1891. He was elected Chairman of the East Midland Sub-Centre for the session 1923–24, but owing to his tragic death at Bournemouth station on the 24th September he never actually occupied the chair. A man of sterling character, keen in his profession, kind and unassuming in disposition, his sudden death has created a deep sense of loss in a wide circle.

GEORGE RICHARD WEBB, who died in London on the 30th November, 1922, after an operation, was the eldest son of the late Francis Hughes Webb, for many years Secretary of the Institution. He received his early training in electrical matters at the old G.P.O. instrument factory in Gloucester-road, where he acquired a sound knowledge of the telegraph apparatus in use 40 years ago. In 1888, at the age of 24, he was appointed assistant telegraph superintendent to the Great Indian Peninsula Railway Company and went to Bombay, where he resided until shortly before his untimely death. He was promoted to be stores superintendent of the G.I.P. system some years ago, and in this post rendered admirable service, his uprightness of character and long experience of the technical side of railway work, together with his imperturbable good humour—which the climate of India never quenched—forming most valuable qualifications for the delicate work which falls to the lot of the stores manager of a great railway system. During the European war Mr. Webb served on the Indian Munitions Committee, and his strenuous work in organizing the local supplies for the Mesopotamian campaigns was rewarded by his appointment to the Order of the British Empire. Throughout his life he was an active Volunteer, having been a member of the Artists' Rifle Corps since 1880, and serving during the whole of his residence in India in the Volunteer regiment of the G.I.P. Railway Company, in which he attained the rank of Lieutenant-Colonel. His was a most lovable character ; and his sterling honesty, his unfailing good humour, his kind and generous disposition, and his single-minded devotion to whatever he might be engaged in at the time—work or play—endeared him to all with whom he came in contact. His death, at the comparatively early age of 58, was a severe blow to his many friends and to his relatives. He was twice married and left a widow and two children, a son and a daughter. He was elected an Associate of the Institution in 1889, and a Member in 1891. H. L. W.

HERBERT TATLOCK WILKINSON, whose death occurred on board ship on his trip homeward from India on the 7th May, 1922, was 45 years of age. He had been managing director of the Wardle Engineering Co. since its formation in 1909. He completed his apprenticeship with Messrs. Royce in 1895 and afterwards took up an appointment with the Howard Asphalte Troughing Co., for whom he carried out several large contracts. He was successful in introducing this system into numerous municipalities. His next appointment was with the Lancashire Electric Power Co., leaving this company to take up a post with the Chloride Electrical Storage Co. In 1909 he acquired the business of Cutler, Wardle and Co., in conjunction with Mr. C. H. K. Chamen, who is now the chief electrical engineer of the Jammu and Kashmir State, India. Shortly afterwards the business was registered as a limited liability company under the title of the Wardle Engineering Co. From small beginnings the business rapidly progressed under his guidance. Mr. Wilkinson never spared himself in whatever he undertook, and to his endeavours to further the interests of the company his death is, no doubt, to some degree attributable. Some 10 years ago he took a very prominent part in the formation of the Engineers' Club, Manchester, being appointed on the general committee. In this connection he performed his duties in a wholehearted fashion, and upon the resignation of Mr. Edmund L. Hill in 1917 from the honorary secretaryship, Mr. Wilkinson was unanimously elected to fill the post, which he ultimately had to resign on account of pressure of business. Subsequently Mr. Wilkinson removed to London, and, recognizing the advantages of the Manchester Club to the engineers of the district, he was one of the first to agitate for a similar club in London. The result of this agitation was the formation of the Engineers' Club, London, which was opened in August 1921. Mr. Wilkinson was a man with a charming personality and had a large circle of friends, by whom he was held in the highest esteem. He left a widow and three sons. He was elected an Associate of the Institution in 1901, an Associate Member in 1904, and a Member in 1916. H. R.

# THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 35. Dec. 1922. INSTITUTION NOTES. [ISSUED WITH No. 313 OF THE JOURNAL.]

## Honorary Member.

At the Ordinary Meeting of the Institution on the 16th November the President announced that the Council had elected Professor J. A. Fleming, M.A., D.Sc., F.R.S., an Honorary Member of the Institution.

## Anti-Aircraft Battalion, Royal Engineers (T.A.).

The Secretary of the Institution has been requested to give publicity to the following:

Members of the Institution are invited to make application to join the recently formed (11th) A.A. Battalion, Royal Engineers (Territorial Army), whose duties will include the manning of searchlights, sound locaters and observer sections connected with the air defences of London. This unit, which is under the command of Lieut.-Colonel K. Edgcumbe, late of the London Electrical Engineers, is closely identified with that Corps and has taken over its former headquarters in Regency-street, Westminster. The Battalion comprises four companies and about 800 of all ranks. Practically all the officers, and a very large proportion of other ranks, were members of the Corps of London Electrical Engineers.

In view of the fact that the Corps of London Electrical Engineers was founded by the late Dr. John Hopkinson, then President, under the patronage of the Institution, the Officer Commanding hopes that every member of the Institution will do his utmost to encourage the younger members to join the new Battalion, and thus, in the words of Lord Kelvin, the first Hon. Colonel of the London Electrical Engineers, "promote the utilization of the patriotism and abilities of electrical engineers for national defence."

Full particulars can be obtained from the headquarters of the Battalion, 46 Regency-street, Westminster, S.W. 1.

## Associate Membership Examination Results (October, 1922).

*Passed.*

Atkins, R. E.
Austin, C.
Bleach, C. C.
Cameron-Kirby, C.
Debley, W. J. F.
Gorton, E. J.
Gresswell, W. F.
Herbert, E. D. A.
Hine, F. W.
Jones, I. L.
Lye, D. H. C.
McClean, T.
Morrish, H. E.
Pennell, E. R.
Smith, C. H.
Taylor, E. H.
Telfer, F. P. G.
Waizbom, H.
Wilkins, C.
Williams, T.

*Passed in Part II.*

Badhni-Valla, J. N.
Braendle, E. W.
Randall, A. J.
West, F. W. J.
Wright, R.

*Passed in Part I.*

Bee, O. K.
Weston, N. C.

[The results relating to candidates who sat for the Examination abroad will be published later.]

### Officers of Corps of Royal Engineers.

*Passed.*

Abraham, 2nd Lieut. T. E.
Bader, Lieut. E.
Baker, 2nd Lieut. G. L.
Benner, 2nd Lieut. P. K.
Beyts, 2nd Lieut. W. D. H.
Bourne, 2nd Lieut. H. J.
Carden, 2nd Lieut. P. B. H.
Cavendish, 2nd Lieut. H. P.
Chase, Lieut. J. L. H.
Chevis, Lieut. W. J. C.
Churchill, Lieut. A. R.
Clark, 2nd Lieut. G. C.
Clarke, 2nd Lieut. G. G. S.
Cleeve, 2nd Lieut. D. W. A.
Cole, 2nd Lieut. W. S.
Colvin, 2nd Lieut. E.
Cook, 2nd Lieut. E. F. B.
Davidson-Houston, 2nd Lieut. J. V.
Doelberg, 2nd Lieut. J. F.
Drake-Brockman, 2nd Lieut. A. G.
Fraser, 2nd Lieut. D. G.
Freeman, 2nd Lieut. R. C.
Gayer, Lieut. E. H. T.
Hancock, 2nd Lieut. L. F.
Havers, 2nd Lieut. R. H.
Healing, 2nd Lieut. W. R.
Hext, 2nd Lieut. F. M.
Holloway, 2nd Lieut. R. E.
Hudson, 2nd Lieut. S. G.
Jennings, 2nd Lieut. G. W. D.
Kay, 2nd Lieut. H. S.
Laurence, 2nd Lieut. E. R.
Laurence, 2nd Lieut. R. A.
Leese, 2nd Lieut. J. F. M.
Logan, 2nd Lieut. A. R.
Lowe, 2nd Lieut. J. H. B.
Lucas, 2nd Lieut. A. R. S.
McCandlish, 2nd Lieut. J. E. C.
Macdonald, 2nd Lieut. D. G. G.
McDonald, 2nd Lieut. E.
Mackay, 2nd Lieut. K.
McMullen, 2nd Lieut. D.
MacTier, 2nd Lieut. K. F.
Martin, 2nd Lieut. C. J. M.
Millar, 2nd Lieut. R. K.
Moscardi, 2nd Lieut. H. L.
Moss, 2nd Lieut. G. H. B.
Oborne, 2nd Lieut. T. D.
O'Donnell, 2nd Lieut. H. M.
Palmer, 2nd Lieut. G. A.
Philbrick, 2nd Lieut. G. E. H.
Prentice, 2nd Lieut. M. R. R.
Ransford, Capt. A. J.
Rycroft, 2nd Lieut. D. M.
Saegert, 2nd Lieut. J. M.
Scullard, 2nd Lieut. H. R.
Smith, 2nd Lieut. W. A. R.
Steel, 2nd Lieut. C. D.
Stowell, 2nd Lieut. E. C. S.
Stowell, 2nd Lieut. L. H.
Swettenham, 2nd Lieut. N. A. M.
Tuck, 2nd Lieut. G. N.
Veitch, 2nd Lieut. W. L. D.
Walker, 2nd Lieut. A. A. C.
Whitehorn, 2nd Lieut. E. W. L.
Wilkinson, 2nd Lieut. P. L.
Wright, 2nd Lieut. H. W.

## Committees, 1922–1923.

Among the Committees appointed by the Council for 1922–23 are the following:—

### INFORMAL MEETINGS.

The President.

Mr. J. F. Avila.
Mr. J. R. Bedford.
Mr. A. B. Eason.
Mr. R. Grierson.
Mr. A. F. Harmer.
Mr. E. F. Hetherington.
Mr. E. W. Moss.
Mr. F. Pooley.
Mr. W. E. Warrilow.

And

The Chairman of the Papers Committee.
The Chairman of the London Students' Section.

### LIBRARY AND MUSEUM.

The President.

Colonel R. E. Crompton, C.B.
Mr. P. V. Hunter, C.B.E.
Prof. E. W. Marchant, D.Sc.
Mr. W. M. Mordey.
Sir A. M. Ogilvie, K.B.E., C.B.
Mr. C. C. Paterson, O.B.E.

### LOCAL CENTRES.

The President.

Mr. F. G. C. Baldwin.
Mr. A. S. Barnard.
Prof. W. Cramp, D.Sc.
Sir J. Devonshire, K.B.E.
Mr. A. S. Hampton.
Mr. E. C. Handcock.
Mr. J. S. Highfield.
Mr. P. V. Hunter, C.B.E.
Prof. E. W. Marchant, D.Sc.
Sir W. Noble.
Mr. A. Page.
Mr. F. Tremain.
Mr. C. H. Wordingham, C.B.E.

### "SCIENCE ABSTRACTS."

The President.

Mr. Ll. B. Atkinson.
Mr. W. M. Mordey.
Mr. C. C. Paterson, O.B.E.
Dr. A. Russell.

| *And* | *Representing* |
|---|---|
| Dr. D. Owen<br>Mr. T. Smith | The Physical Society of London. |

### SHIP ELECTRICAL EQUIPMENT.

The President.

Mr. J. H. Collie.
Mr. B. M. Drake.
Mr. A. Henderson.
Mr. J. W. Kempster.
Mr. J. F. Nielson.
Mr. N. W. Prangnell.
Major A. P. Pyne.
Mr. S. G. C. Russell.
Mr. T. A. Sedgwick.
Mr. C. H. Wordingham, C.B.E.

| *And* | *Representing* |
|---|---|
| Sir W. S. Abel, K.B.E.<br>Mr. J. T. Milton | Lloyd's Register of Shipping. |
| Two representatives | British Electrical and Allied Manufacturers' Association. |
| Mr. T. Carlton | Board of Trade. |
| Mr. W. Cross | Electrical Contractors' Association. |
| Mr. J. Foster King | British Corporation for the Survey and Registry of Shipping. |

### SHIP ELECTRICAL EQUIPMENT—*continued.*

| | |
|---|---|
| Mr. J. Lowson | Institution of Engineers and Shipbuilders in Scotland.<br>Electrical Contractors' Association of Scotland. |
| Mr. A. W. Stewart | Institution of Naval Architects. |
| Mr. H. Walker, O.B.E. | N.E. Coast Institution of Engineers and Shipbuilders. |

### WIRELESS SECTION.

Professor G. W. O. Howe, D.Sc. (*Chairman*).

The President.

Mr. B. Binyon, O.B.E.
Mr. S. Brydon, D.Sc.
Mr. R. C. Clinker.
Dr. W. H. Eccles, F.R.S.
Prof. C. L. Fortescue, O.B.E.
Mr. G. H. Nash, C.B.E.
Mr. C. C. Paterson, O.B.E.
Mr. J. St. Vincent Pletts.
Capt. H. J Round, M.C.
Dr. A. Russell.
Capt. H. R. Sankey, C.B., C.B.E., R.E.
Mr. R. L. Smith-Rose.
Mr. A. A. C. Swinton, F.R.S.
Mr. L. B. Turner.

| *And* | *Representing* |
|---|---|
| Capt. C. E. Kennedy-Purvis, R.N. | Admiralty. |
| Lt.-Col. H. Clementi Smith, D.S.O. | War Office. |
| Major H. P. T. Lefroy, D.S.O., M.C. | Air Ministry. |
| Mr. E. H. Shaughnessy, O.B.E. | Post Office. |

### WIRING RULES.

The President.

Mr. Ll. B. Atkinson.
Mr. J. W Beauchamp.
Mr. H. J. Cash.
Mr. J. R. Cowie.
Mr. W. Cross.
Mr. J. Frith.
Dr. C. C. Garrard.
Mr. P. V. Hunter, C.B.E
Mr. S. W. Melsom.
Mr. J. F. Nielson.
Major A. P. Pyne.
Mr. E. Ridley.
Mr. C. P. Sparks, C.B.E.
Mr. C. H. Wordingham, C.B.E.

| *And* | *Representing* |
|---|---|
| Mr. E. G. Batt<br>Mr. H. H. Berry<br>Mr. J. R. Dick<br>Mr. A. R. Everest<br>Mr. C. Rodgers | British Electrical and Allied Manufacturers' Association. |
| Mr. W. F. Bishop | Cable Makers' Association. |
| Sir T. O. Callender<br>Mr. J. F. W. Hooper | Cable Makers (unofficially). |
| Mr. W. R. Rawlings<br>Mr. S. H. Webb | Electrical Contractors' Association. |
| Mr. E. J. B. Lowdon | Electrical Contractors' Association of Scotland. |
| Mr. B. M. Drake | Contractors (unofficially). |
| Mr. A. C. Cockburn<br>Mr. S. G. C. Russell<br>Mr. A. L. Taylor | Fire Offices (unofficially). |
| Mr. J. Christie<br>Mr. F. W. Purse | Incorporated Municipal Electrical Association. |
| Mr. E. T. Ruthven Murray | Incorporated Association of Electric Power Companies. |
| Mr. O. M. Andrews | Conference of Chief Officials of the London Electric Supply Companies. |
| Mr. J. M. Crowdy | Association of Supervising Electricians. |

## SECTIONAL COMMITTEES.

### Lighting and Power.

The President.

Mr. J. W. Beauchamp.
Mr. J. R. Bedford.
Mr. R. A. Chattock.
Mr. R. Grierson.
Mr. A. F. Harmer.
Mr. E. T. Ruthven Murray.
Mr. A. Page.
Mr. G. W. Partridge.
Mr. C. P. Sparks, C.B.E.
Mr. W. B. Woodhouse.

### Electricity in Mines.

The President.

Mr. W. A. Chamen.
Dr. C. C. Garrard.
Mr. J. A. B. Horsley.
Mr. W. C. Mountain.
Mr. W. H. Patchell.
Mr. W. M. Selvey.
Mr. C. P. Sparks, C.B.E.
Prof. W. M. Thornton, D.Sc., O.B.E.
Mr. W. B. Woodhouse.

### Traction.

The President.

Sir J. Devonshire, K.B.E.
Mr. H. W. Firth.
Lt.-Col. F. A. Cortez Leigh.
Mr. F. Lydall.
Mr. A. H. W. Marshall.
Mr. G. W. Partridge.
Mr. J. Sayers.
Mr. R. T. Smith.
Mr. B. Welbourn.

### Electro-Chemistry and Electro-Metallurgy.

The President.

Mr. W. A. Chamen.
Mr. W. R. Cooper.
Prof. W. Cramp, D.Sc.
Mr. S. E. Fedden.
Mr. W. M. Mordey.
Mr. W. M. Morrison.
Mr. J. Swinburne, F.R.S.,
and 2 members to be co-opted by the Committee.

### Telegraphs and Telephones.

The President.

Sir Charles Bright, F.R.S.E.
Mr. H. G. Brown.
Dr. W. H. Eccles, F.R.S.
Mr. S. Evershed.
Mr. H. H. Harrison.
Sir W. Noble.
Mr. T. F. Purves.
Mr. F. Ryan.
Mr. J. Sayers.
Mr. F. Tremain.

## Representatives of The Institution on Other Bodies.

The following is a list of representatives of the Institution on other bodies and the dates on which they were appointed.

**Birmingham Chamber of Commerce:**
Mr. S. T. Allen (27 March, 1919).

**Bradford Public Libraries Committee:**
Mr. T. Roles (27 Feb., 1919).

**Bristol University:**
Mr. H. F. Proctor (6 Dec., 1917).

**British Electrical and Allied Industries Research Association:**
Mr. Ll. B. Atkinson (2 April, 1919).
Dr. C. C. Garrard (30 Oct., 1919).
Mr. F. Gill, O.B.E. (2 Nov., 1922).
Mr. C. C. Paterson, O.B.E. (4 Oct., 1917).
Mr. R. T. Smith (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (4 Oct., 1917).
Mr. C. H. Wordingham, C.B.E. (4 Oct., 1917).

*Sectional Committee on 'Electric Control Apparatus Research :*
Mr. C. H. Wordingham, C.B.E. (22 Nov., 1920).
Major H. C. Gunton (2 Feb., 1921).

**British Electrical Development Association:**
Mr. R. Hardie (27 Jan., 1921).
Mr. H. J. Cash (19 Jan., 1922).
Mr. C. H. Wordingham, C.B.E. (18 Sept., 1919).

**British Empire Exhibition, 1924 (Electrical and Allied Engineering Committee):**
Sir A. M. Ogilvie, K.B.E., C.B. (23 June, 1922).

**British Engineering Standards Association:**

*Main Committee :*
Col. R. E. Crompton, C.B. (2 April, 1914).
Sir John Snell (2 April, 1914).
Mr. C. H. Wordingham, C.B.E. (26 Feb., 1920).

*Sectional Electrical Committee :*
Mr. F. Gill, O.B.E. (21 May, 1914).
Mr. J. S. Highfield (21 May, 1914).
Mr. R. T. Smith (21 May, 1914).
Mr. W. B. Woodhouse (19 Dec., 1918).
Mr. C. H. Wordingham, C.B.E. (18 Nov., 1915).

*Sectional Committee on British Standards in Colonial and Foreign Trade :*
Mr. C. P. Sparks, C.B.E. (26 Oct., 1916).

*Sectional Committee on Machine Parts and their Gauging and Nomenclature :*
Mr. J. H. Rider (8 Feb., 1917).

*Electrical Nomenclature and Symbols Sub-Committee :*
Mr. C. C. Paterson, O.B.E. (8 Jan., 1920).

*Overhead Transmission Lines Material Sub-Committee :*
Mr. C. H. Wordingham, C.B.E. (30 Oct., 1919).

*Pipe Flanges Sub-Committee :*
Mr. W. M. Selvey (14 April, 1921).

*Panel on Steel Conduits for Electric Wiring :*
Mr. H. J. Cash (28 Sept., 1922).
Mr. J. M. Crowdy (28 Sept., 1922).

*Conference on Standardization of Ball and Roller Bearings :*
Mr. W. M. Selvey (26 July, 1921).

**Corrosion Research Committee, Institute of Metals:**
Mr. W. M. Selvey (18 May, 1922).

**Darlington Board of Invention and Research:**
Mr. R. M. Longman (15 May, 1919).
Mr. J. R. P. Lunn (15 May, 1919).
Mr. H G. A. Stedman (15 May, 1919).

**Fuel Economy Committee, British Association:**
Mr. C. H. Wordingham, C.B.E. (9 Jan., 1919).

**Imperial College of Science and Technology, Governing Body:**
Mr. W. M. Mordey (30 Oct., 1919).

**Imperial Mineral Resources Bureau Conference:**
Mr. J. H. Rider (23 Jan., 1919).
Mr. W. B. Woodhouse (23 Jan., 1919).

*Copper Committee :*
Mr. B. Welbourn (18 Sept., 1919).

*Miscellaneous Minerals Committee :*
Prof. E. Wilson (18 March, 1920).

**Institution of Civil Engineers, Engine and Boiler Testing Committee:**
Mr. R. A. Chattock (19 Oct., 1922).
Mr. C. P. Sparks, C.B.E. (19 Oct., 1922).

**International Illumination Commission, British National Illumination Committee:**
Prof. W. C. Clinton (13 Dec., 1917).
Mr. K. Edgcumbe (27 Nov., 1913).
Mr. Percy Good (18 Sept., 1919).
Mr. H. T. Harrison (27 Nov., 1913).
Prof. J. T. MacGregor-Morris (27 Nov., 1913).

**International Navigation Congress, 1923, General Organization Committee:**
Mr. F. Gill, O.B.E. (2 Feb., 1922).

**International Scientific Unions:**

*Committee on International Union in Physics :*
Dr. A. Russell (18 March, 1920).

*Committee on International Union in Radio-Telegraphy :*
Dr. W. H. Eccles, F.R.S. (18 March, 1920).
Prof. G. W. O. Howe, D.Sc. (18 March, 1920).
Prof. E. W. Marchant, D.Sc. (18 March, 1920).

**International Smoke Abatement Exhibition, 1922:**
Mr. J. W. Beauchamp (26 July, 1921).
Mr. J. S. Highfield (26 July, 1921).

**Leeds Civic Society:**
Mr. E. C. Wallis (27 March, 1919).

**Leeds Municipal Technical Library Committee:**
Mr. W. B. Woodhouse (19 Dec., 1918).

**Metalliferous Mining (Cornwall) School, Governing Body:**
Mr. J. S. Highfield (18 Sept., 1919).

**Munitions Inventions Department, Nitrogen Products Committee:**
Sir John Snell (12 Oct., 1916).

**Munitions, Ministry of, Disposal of Surplus Government Property:**
Mr. J. S. Highfield (13 Feb., 1919).

**National Committee for Physics (Royal Society):**
Dr. A. Russell (16 Dec., 1920).

**National Committee in Radio-Telegraphy (Royal Society):**
Dr. W. H. Eccles, F.R.S. (4 Aug., 1920).
Prof. E. W. Marchant, D.Sc. (4 Aug., 1920).

**National Physical Laboratory, General Board:**
Mr. Ll. B. Atkinson (21 Oct., 1920).
Mr. C. H. Wordingham, C.B.E. (22 Nov., 1917).

**Paris Conference on E.H.T. Lines:**
Mr. P. V. Hunter, C.B.E. (26 July, 1921).
Mr. E. B. Wedmore (26 July, 1921).
Mr. W. B. Woodhouse (26 July, 1921).

**Paris Conference on Weights and Measures:**
Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S. (14 April, 1921).
Dr. A. Russell (14 April, 1921).

**Professional Classes Aid Council:**
Mr. W. B. Esson (26 July, 1921).

**Röntgen Society Advisory Committee for British X-ray Industry:**
Dr. W. H. Eccles, F.R.S. (21 Feb., 1918).
Mr. J. E. Taylor (21 Feb., 1918).

**Royal Engineer Board:**
Mr. C. H. Wordingham, C.B.E. (7 April, 1921).

**Scientific and Industrial Research Advisory Council, Engineering Committee:**
Mr. J. S. Highfield (9 March, 1916).

**Scientific Societies, Conjoint Board of:**
Mr. C. C. Paterson, O.B.E. (9 Dec., 1920).
Dr. A. Russell (9 Dec., 1920).

*Education Committee :*
Dr. A. Russell (12 Oct., 1916).

**Society of Radiographers:**
Dr. A. Russell (25 May, 1922).

**Transport Ministry, Advisory Panel and Committees:**
Mr. Ll. B. Atkinson (30 Oct., 1919).
Sir J. Devonshire, K.B.E. (30 Oct., 1919).
Mr. J. S. Highfield (30 Oct., 1919).
Mr. R. T. Smith (30 Oct., 1919).
Sir John Snell (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (30 Oct., 1919).
Mr. C. H. Wordingham, C.B.E. (30 Oct., 1919).

**War Office Committee on Engineer Organization:**
Mr. C. H. Wordingham, C.B.E. (10 April, 1919).

**Women's Engineering Society:**
Mr. A. P. M. Fleming, C.B.E. (14 April, 1921).

# THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 36. Jan. 1923. INSTITUTION NOTES. [ISSUED WITH No. 314 OF THE JOURNAL.]

## Local Honorary Secretaries Abroad.

The Council have appointed Mr. Gano Dunn to be Local Honorary Secretary of the Institution for the United States of America, and Mr. M. L. Kristiansen for Norway.

## Summer Meeting, 1923.

The Council have accepted an invitation from the Committee of the North-Western Centre to hold a Summer Meeting of the Institution in Manchester, Liverpool and North Wales from 5th to 8th June, 1923. Full particulars will be circulated later.

## Members Visiting the U.S.A.

The attention of members is drawn to an arrangement between the Institution and the American Institute of Electrical Engineers for the mutual granting of facilities and privileges as Visiting Members to members of the two societies visiting each other's country.

Members who intend to visit the United States of America and wish to avail themselves of this arrangement should apply to the Secretary of the Institution for a letter of introduction to the American Institute of Electrical Engineers, stating in what branch of the profession they are engaged and giving the name of the firm or company (if any) with which they are connected.

## International Conference on E.H.T. Power Transmission.

The Proceedings of the above Conference, which was held at Paris in November, 1921, and at which 12 countries were represented, have recently been published by the Union des Syndicats de l'Electricité.

The Proceedings comprise 1 200 pages and 350 illustrations, and contain: (1) an introductory note in regard to the aims and work of the Conference; (2) a general account of the proceedings by M. Boucherot; (3) the full text of the 68 Reports presented to the Conference; and (4) revised reports of the discussions.

The Proceedings will not be reprinted, and only a limited number of copies will be available for non-subscribers to the Conference. Any member of the Institution desirous of obtaining a copy should therefore make early application to the Union des Syndicats de l'Electricité, 25, Boulevard Malesherbes, Paris. The price is 100 francs per copy.

## Informal Meetings.

The following Informal Meetings have been held:—

### 33rd Informal Meeting (6th November, 1922).

*Chairman*: Mr. F. Gill, O.B.E.

*Subject of Discussion*: "The Importance of Commercial Knowledge to the Engineer" (introduced by Mr. F. Gill, President).

*Speakers*: Messrs. F. Pooley, W. E. Rogers, F. H. Masters, L. W. Phillips, W. H. Lawes, R. W. Hughman, A. Wright, A. F. Harmer, P. Rosling, G. V. Twiss, P. Dunsheath, E. F. Hetherington, R. C. Andersen, F. A. Sclater, R. Grierson, and A. Rosen.

### 34th Informal Meeting (20th November, 1922).

*Chairman*: Mr. W. E. Warrilow.

*Subject of Discussion*: "Electric Light Wiring" (introduced by Mr. F. J. Pearce).

*Speakers*: Messrs. F. Peake Sexton, A. F. Harmer, W. E. Rogers, W. L. Wreford, W. F. Bishop, P. Rosling, W. Fanghanel, E. H. Freeman, L. M. Jockel, A. G. Hilling, A. T. Smee, E. Turle, C. J. Banster, P. Dunsheath, F. E. Phillips, P. D. Dale, M. Whitgift, C. T. Walrond, J. R. Bedford, G. J. D. Scott, and W. E. Warrilow.

### 35th Informal Meeting (4th December, 1922).

*Chairman*: Mr. J. F. Avila.

*Subject of Discussion*: "An Electrical Installation at a Model Farm" (introduced by Mr. F. A. Sclater).

*Speakers*: Messrs. R. Borlase Matthews, W. E. Rogers, H. F. Young, J. Coxon, C. A. Edwards, W. J. Minton, A. H. Dixon, W. E. Warrilow, C. T. Walrond, A. G. Hilling, P. Dunsheath, J. F. Caine, F. Pooley, W. L. Wreford, J. R. Bedford, B. Shallis, E. B. Rook, and H. W. Richardson.

### 36th Informal Meeting (18th December, 1922).

*Chairman*: Mr. J. R. Bedford.

*Subject of Discussion*: "Time Switches" (introduced by Mr. E. E. Sharp).

*Speakers*: Messrs. F. B. Nathan, W. L. Wreford, C. T. Walrond, F. Pooley, J. R. Bedford, W. E. Rogers, A. G. Hilling, G. D. Malcolm, A. Kirk, R. V. Hook, H. H. Long, F. R. C. Rouse, J. F. Avila, and G. J. D. Scott.

### 37th Informal Meeting (8th January, 1923).

*Chairman*: Mr. R. Grierson.

*Subject of Discussion*: "The Protection of Inventions by Letters Patent" (introduced by Mr. E. W. Moss).

*Speakers*: Messrs. W. E. Rogers, A. F. Harmer, E. F. Hetherington, J. R. Bedford, P. G. A. H. Voigt, A. G. Evans, W. L. Wreford, C. S. Parsons, J. L. Girling, M. Whitgift, A. S. Carnegie, F. W. Foster, R. V. Hook, C. L. Arnold, G. J. D. Scott, and R. Grierson.

## "Les Annales des Postes, Télégraphes et Téléphones."

The Secretary is informed that the above publication, which for several years past has been issued every two months by the French Post, Telegraph and Telephone Department, will become from the 1st January, 1923, a monthly publication. The price will continue to be 24 francs for subscribers in France, and 27 francs for subscribers abroad. The publishers are La Libraire de l'Enseignment Technique, 3, Rue Thénard, Paris, to whom subscriptions should be sent.

## The British Electrical and Allied Industries Research Association.

### HALF-YEARLY REVIEW OF PROGRESS (JANUARY, 1923).

### Section A: Fibrous Insulating Materials.

*Classification and nomenclature.*—The classification of materials, uses and requirements has now been completed for all the fibrous materials and materials with a fibrous base dealt with hitherto by this Association, thus furnishing a firm foundation for future study. The detailed study of varnishes has only been commenced recently and the classification is incomplete.

*Methods of testing.*—Methods of testing have now been developed for all the materials dealt with and have been fully described in the publications of the Association, the work on varnished fabrics being, however, not quite complete.

*Purchasing specifications.*—Based on the above and the results of the numerous investigations which have been made, the Association is now drafting simplified recommendations applicable to the preparation of British Standard Purchasing Specifications in connection with all the materials in the fibrous group ripe for standardization.

*Improvement of materials.*—As a direct result of the attention given to certain features, improvements can already be recorded in the quality of materials manufactured. Attention is now being directed to the study of specific sources of weakness which have been traced through the work already done, and to the development of new materials having better characteristics.

Attention is being given to shellac, amongst other materials, with a view to obtaining better adhesiveness and temperature characteristics, and comparison is being made with alternative materials.

### Section B: Composite Insulating Materials.

The experimental tests on heat-resisting properties are now practically completed, which will furnish the necessary data for the completion of a specification on these properties. A provisional classification has been made of moulding properties of composite insulating materials, and some attention has been given also to the effect of immersion in insulating oils or contact with lubricating oils.

### Section C: Porcelain.

The Association is awaiting a full report from the investigators, but the following may be noted meanwhile:—

*Electric strength.*—A series of investigations of electric strength under momentary stresses has been practically completed, covering a temperature range from normal to 300° C., and some progress made with tests under prolonged stress.

*Resistivity.*—A large variety of samples varying in composition and mode of manufacture has been tested for resistivity at temperatures from 70° C. up to 1 200° C. Samples suitable for furnace work have not yet been tested.

*Porosity and vitrification.*—Some progress has been made in the study of porosity by electrical methods, and uniformity of vitrification by immersion in water under high pressure.

*Surface deposits.*—The study of surface deposits from the atmosphere has presented unexpected difficulties, but further tests are being made in co-operation with the G.P.O.

*Thermal expansion.*—Tests on thermal expansion have been arranged in co-operation with an interested Government Department.

*Mechanical properties.*—Samples are being obtained for tests on mechanical properties.

### Section D: Mica and Micanite.

*Micas.*—Further tests have brought out important features in the study of mechanical properties of mica, especially flexibility, and a survey of these properties is now being made on a small scale.

*Micanites.*—Methods of studying the properties of micanite have been developed with a view to the production of a purchasing specification, and the elimination of undesirable material. Work is nearly completed on the following: Uniformity and limits of thickness; percentage of moisture, adhesive, mica and reinforcement; quality of splittings; softening temperature; moulding temperature; electric strength; permittivity; surface resistance; tensile strength.

A report on the classification of micanites, with notes on their manufacture, uses and characteristics, is about to be issued.

### Section E: Insulating Oils.

*Electric strength and resistivity.*—The detailed investigation into the relative merits of the horizontal and vertical placing of the spherical electrodes used in electric strength tests has now been completed and has shown that the horizontal arrangement is the better for the purpose.

An attempt is being made to develop a method of testing electric strength eliminating the expensive high-voltage transformer equipment now necessary.

Past research on the effect of the presence of different kinds of impurity on electric strength and resistivity has been reviewed in detail and a new series of researches commenced.

*Centrifugal separation.*—Further tests have been made and arranged for the investigation of the merits of centrifugal separators for oil purification with a view to discovering the technical and commercial limitations of apparatus now available, and assisting in the development of this promising method.

*Sludging tests.*—Opportunity has been taken of the presence in this country of experts from the U.S.A. and the Continent to discuss the methods of sludge testing in use and under development in those countries. Attempts are being made to develop a simpler test than now in use.

*Physical constants.*—Reports have been received on latent heat, vapour pressure, thermal conductivity and specific heat, and are under consideration.

*Thermal transference.*—A report has been received on thermal transference and is under consideration.

### SECTION F : CONDUCTORS.

*Heating of buried cables.*—Good progress has been made in the preparation of the Report on "Permissible Current Loading of British Standard Paper Insulated Electric Cables," being the second report on the research on the heating of buried cables, and it is hoped to present the report to the Institution of Electrical Engineers in a few weeks' time.

*Wood poles for overhead lines.*—A report on the tests made on single **A** and **H** poles has been issued to interested members of the Association. Progress has been made towards clearing up the numerous important questions raised by that report, and a further programme of tests will be put in hand shortly.

*Overhead line materials.*—Reports have been completed on the tests made under working conditions on the mechanical properties of copper and aluminium wires and cables, and galvanized steel and steel-cored aluminium cables, and it is expected that these will be published shortly.

### SECTION G : ELECTRIC CONTROL APPARATUS.

*Phenomena of switching and arcing.*—The researches on oil circuit breakers are now in full activity, a unique installation of testing apparatus having been developed and erected at the Carville power station of the Newcastle-upon-Tyne Electric Supply Co., at a cost of several thousand pounds. The larger part of the original programme of experimental work has already been completed, and in view of the importance of this research to the whole industry, and especially to large users and suppliers of electricity, the Association is appealing for their co-operation so that full advantage may be taken of the exceptional opportunity at present available for further experimental research and development.

*Mining switchgear.*—The researches on the development and relief of pressure in mining switchgear are being continued under the auspices of the Technical Appliances Committee of the Safety in Mines Research Board, and a further report is expected shortly.

*Fusible cut-outs.*—A comprehensive survey of published information on fusible cut-outs has been completed and a critical résumé prepared, which will form a firm foundation for building up future research programmes. A report is in preparation on the tests made on ordinary-duty fusible cut-outs.

*Air-break circuit breakers.*—The continuation of researches on air-break circuit breakers awaits the provision of the necessary facilities.

*Resistivity of joints and contacts.*—Further tests have been made on joints in large installations of switchgear and a report is expected shortly. Arrangements have been made for continuation of the experimental researches at the National Physical Laboratory.

*Research on contactors.*—A programme of endurance tests on contactors has been prepared and the work awaits the provision of the necessary funds.

### SECTION H : CORROSION RESEARCHES.

The Association continues to co-operate with the Institute of Metals, and the researches on corrosion of steam condensers are maintained in full activity. The sixth report of the Corrosion Research Committee has been received, dealing with the nature of corrosive action, the function of colloids in corrosion and the corrosion of copper.

### SECTION J : TURBINE RESEARCHES.

*Nozzles research.*—A further report of the work in which the Association shares is about to be published by the Institution of Mechanical Engineers.

*Blading research.*—The tests arranged on blading material have been practically completed and a report is awaited.

*Properties of steam.*—The researches on the properties of steam at high temperatures and pressures are in full activity, and other work bearing on the behaviour of steam in turbines.

### SECTION K : SYNTHETIC RESINS.

*Varnish-paper boards and tubes.*—A series of tests carried out on samples from a variety of sources has shown very wide divergences of quality. Further tests are now being carried out on the more promising materials, especial attention being given to the electrical characteristics at radio frequencies and to the mechanical properties. As the result of these tests manufacturers are giving close attention to features which have been shown capable of marked improvement.

*Moulded materials.*—A representative collection of samples from British and foreign sources has now been made and an experimental investigation put in hand, in which the Royal Aircraft Establishment is co-operating.

### SECTION L : DIELECTRICS IN GENERAL.

*Dielectric losses.*—The investigation on dielectric losses has now been extended to radio frequencies, especial attention being given to the synthetic resin products. Work on micas has been practically completed, and a report is expected shortly on varnished fabrics.

Good progress has been made in the development and application of cathode ray tubes.

*Thermal resistivity.*—A considerable number of further measurements of thermal resistivity have been made showing the effect of different methods of construction of the finished product. Shortage of funds will necessitate this important investigation being brought to a close at an early date.

*Effect of heat on electrical insulating materials.*—Recommendations for the classification and nomenclature of the heat-resisting properties of dielectrics have been prepared and transmitted to the interested Committees of the British Engineering Standards Association and the Institution of Electrical Engineers. Methods of test are being developed and made applicable to the whole range of materials in question. The same procedure is being extended to cover the effect of temperature on the electrical and mechanical properties.

*Electric strength.*—A preliminary report has been received on the tests made to show the relative accuracy of certain laboratory and workshop methods of testing electric strength, and bringing out some quite unexpected and important features which are receiving further attention.

Comprehensive recommendations are in preparation covering methods of testing the electric strength of all kinds of insulating materials.

### SECTION M: WAVE-FORM.

The preparation of a programme of experimental work awaits the results of further study of what has been done elsewhere.

### SECTION Z: UNCLASSIFIED.

*Die castings.*—The Association is co-operating with others in preparing a scheme of research for improvements in the manufacture and use of die castings.

*Flicker in electric lamps.*—An investigation has been made into the limiting conditions under which objectionable flicker is produced in electric lamps by cyclic variations of supply voltage.

## Accessions to the Lending Library.

AVERY, A. H. Dynamo design and construction. 8vo. 263 pp. *London, n.d.*

BROUGHTON, H. H. The electric handling of materials. vol. 3, Electric cranes. 4to. 352 pp. *London,* 1922

CARSLAW, H. S. Introduction to the mathematical theory of the conduction of heat in solids. 2nd ed. 8vo. 280 pp. *London,* 1921

CARTER, F. W. Railway electric traction. 8vo. 420 pp. *London,* 1922

CUSHING, H. C., *jr.* The electric vehicle hand-book. sm. 8vo. 388 pp. *New York,* [1918]

FEW, H. P. Elementary determinants for electrical engineers. sm. 8vo. 98 pp. *London,* [1922]

GOUDIE, W. J., *D.Sc.* Steam turbines. 2nd ed. 8vo. 822 pp. *London,* 1922

KEARTON, W. J. Steam turbine theory and practice. 8vo. 472 pp. *London,* 1922

KEEN, R. Direction and position finding by wireless. 8vo. 376 pp. *London,* 1922

KEMP, P. Alternating current electrical engineering. [2nd ed.] 8vo. 526 pp. *London,* 1922

LAWRENCE, R. R. Principles of alternating currents. 8vo. 446 pp. *New York,* 1922

MAIN, F. W. Electric cables: a practical treatise on the construction, properties, installation, and maintenance of electric cables. For junior engineers, students, and those in charge of works and factories. sm. 8vo. 111 pp. *London,* 1922

MATTHIS, A. R. Insulating varnishes in electrotechnics. Preface by E. Piérard. Transl. by A. Russell. 8vo. 283 pp. *Manchester,* [1922]

MEARES, J. W., *C.I.E.* The law relating to electrical energy in India. 2nd ed., revised. 8vo. 403 pp. *Calcutta,* 1922

MITTELL, B. E. G. Continuous wave wireless telegraphy. sm. 8vo. 129 pp. *London,* 1922

POOLE, H. E. Switching and switchgear. sm. 8vo. 127 pp. *London,* 1922

PRICE, H. W., and DUFF, C. K. Papers on current transformers. (University of Toronto, School of Engineering Research, Bulletin No. 2, 1921.) 8vo. 65 pp. *Toronto,* 1921

RASCH, E. Electric arc phenomena. Transl. by K. Tornberg. 8vo. 210 pp. *New York,* 1913

ROBINSON, S. M., *U.S.N.* Electric ship propulsion. 8vo. 280 pp. *New York,* [1922]

SCOTT-TAGGART, J. Elementary text-book on wireless vacuum tubes. 4th ed. 8vo. 262 pp. *London,* [1922]

SMITH, C. F. The testing of transformers and alternating current machines. sm. 8vo. 102 pp. *London,* 1922

TATTERSALL, A. E. Modern developments in railway signalling. A treatise dealing with the theory and application of—(1) Track-circuiting; (2) Power signalling, and (3) Automatic train control. 8vo. 299 pp. *London,* 1921

TAYLOR, W. T. Electric power systems. sm. 8vo. 119 pp. *London,* 1922

VAN DER BIJL, H. J. The thermionic vacuum tube and its applications. 8vo. 410 pp. *New York,* [1920]

WANAMAKER, E., and PENNINGTON, H. R. Electric arc welding. 8vo. 265 pp. *New York,* [1921]

# THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 37. March 1923.

## INSTITUTION NOTES.

[ISSUED WITH No. 316 OF THE JOURNAL.]

### Faraday Medal.

At the Council Meeting held on the 15th February the second award of the above Medal was made to the Hon. Sir Charles Algernon Parsons, K.C.B., F.R.S., Honorary Member of the Institution.

### War Thanksgiving Education and Research Fund (No. 1).

The Council have made a grant for 1923 in connection with the above Fund to Mr. R. H. Holmes, a student at the Armstrong College, Newcastle-upon-Tyne.

### War Memorial Fund Scholarships.

Out of the balance of the above Fund it has been decided to establish two scholarships, each of the value of £50 per annum and tenable for three years, to provide for the education of children of members of the Institution who were killed or permanently disabled in the late War.

Applications, giving full particulars as to general and financial circumstances, should be addressed to the Secretary of the Institution, Savoy-place, Victoria-embankment, W.C. 2.

### Annual Conversazione.

The Annual Conversazione will be held at the Natural History Museum, South Kensington, by permission of the Trustees of the Museum, on Thursday, 28th June, 1923.

### Ordinary Meeting, 12 April, 1923.

At the Ordinary Meeting on the 12th April, when a lecture will be given by Mr. A. G. Warren on "X-rays in Theory and Practice," Mr. E. E. Brooks will show at the conclusion of the lecture a few slides illustrating lines of electric force.

### Associate Membership Examination Results (October, 1922).

Supplementary List.*

*Passed :*

| | |
|---|---|
| Jenkin, R. M. | (New Zealand). |
| Williams, V. E. | (South Africa). |
| Witt, S. H. | (Melbourne, Australia). |

### Specification of British Plant and Material.

At a meeting of the Council held on the 1st February, 1923, the following Resolution was passed :—

> "That in view of the present state of trade and employment the Council request members who place or who advise upon the placing of orders to specify as far as practicable that the plant and material ordered shall be of British manufacture."

### International Conference on E.H.T. Lines.

The Council have appointed the following to be the representatives of the Institution at the above Conference, which will be held in Paris next October :—

Mr. W. B. Woodhouse (Senior Delegate),
Mr. P. V. Hunter, C.B.E.,
Mr. E. B. Wedmore.

In addition to the official Delegates, it is understood that the Conference will welcome the attendance of other representatives from each country taking part. Such unofficial representatives will be eligible to take part in the discussions. Those wishing to attend should send their names to M. Tribot-Laspière, 25 Boulevard Malesherbes, Paris.

### Electrical Appointments Board.

The Council again desire to call attention to the Electrical Appointments Board the object of which is to find positions for unemployed members.

During the past year there has been a gradual increase in the number of applicants for posts, particularly Students who have completed their college courses.

A classified Register of such members, containing particulars of their training and experience, is available for inspection at the Institution offices and the Secretary of the Board will gladly put employers into touch with highly qualified electrical engineers in practically all branches of the profession.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the Register. Vacancies may also be reported to the Honorary Secretaries of Local Centres and Sub-Centres who will at once report such vacancies to the Secretary of the Board at the Institution Offices.

---

* See Institution Notes, No. 35, page 1, December, 1922.

## Economics of Engineering Design.

The Secretary will be glad to receive from members, for use in the Institution Library, references to books or articles dealing with or referring to the economics of engineering design.

## Royal Engineers Old Comrades' Association.

Major-General Sir G. K. Scott-Moncrieff, K.C.B., K.C.M.G., C.I.E., President of the Central Committee of the Royal Engineers Old Comrades' Association, desires to ask members of the Institution, particularly ex-Royal Engineers, to assist the Association in finding employment for a large number of skilled men who have served with the R.E. Corps and whose names are now on the Employment Register of the Association.

The requirements of firms seeking reliable men will receive the prompt attention of the Association, and every effort will be made to provide trustworthy men to fill any positions offered. Men skilled in various branches of the engineering industry (including foremen of works, mechanists, electricians, store and ledger keepers, clerks, draughtsmen, instructors in field engineering, surveyors, etc.) are available and the Secretary of the Association, Mr. J. McB. Robbins, Army and Navy Mansions, 109 Victoria-street, London, S.W. 1, will be glad to receive particulars of vacancies.

## Members from the Dominions and Colonies Visiting the United Kingdom.

Members from the Dominions and Colonies visiting the United Kingdom who wish to be put into touch with members of the Institution at home are invited to communicate with the Secretary, stating in what branch of the profession they are engaged and giving the name of the firm or company (if any) with which they are associated.

In this connection the Council have set up an "English-Speaking Nations Committee" whose principal duty is to take an interest in such members and visiting members from the American Institute of Electrical Engineers,

## Removal from Institution Register.

At a meeting held on the 1st March, 1923, the Council ordered the name of Mr. Walter Talbot Kerr to be removed from the Register of the Institution in pursuance of Bye-Law 41 (a).

## Accessions to Reference Library.

Adams, H. Structural design in theory and practice. 2nd ed. 8vo. 265 pp. *London*, 1923

Admiralty, The. Admiralty handbook of wireless telegraphy. 8vo. 485 pp. *London*, 1920

Ainsley, F. J. Mast and aerial construction for amateurs, together with the method of erection and other useful information. sm. 8vo. 86 pp. *London*, 1922

Allen, A. H. Electricity in agriculture. sm. 8vo. 127 pp. *London*, 1922

American Rolling Mill Company. Research and methods of analysis of iron and steel at Armco. 2nd ed. 8vo. 220 pp. *Middletown, Ohio*, 1920

Andrews, E. S. Alignment charts. Their principle and application to engineering formulæ. sm. 8vo. 32 pp. *London*, [1915]

Bagnall-Wild, *Brig.-Gen.* R. K., Aitchison, L., Remington, A. A., Rowledge, A. J., and Thain, W. A. Aircraft steels and material. With an introduction by Prof. W. Ripper. 8vo. 216 pp. *London*, 1922

Behrend, B. A. The induction motor and other alternating current motors. Their theory and principles of design. 2nd ed. 8vo. 295 pp. *New York*, 1921

British Columbia: Bureau of Mines. Annual report of the Minister of Mines for the year ending 31st December, 1921, being an account of mining operations for gold, coal, etc., in the Province. la. 8vo. 365 pp., plates, maps, 1921. *Victoria, B.C.*, 1922

British Electrical and Allied Manufacturers' Association, The. Terms of educational scholarships in electrical and mechanical engineering. 8vo. 8 pp. *London*, 1922

Brownlie, D. Boiler plant testing. 8vo. 179 pp. *London*, 1922

Carter, F. W. Railway electric traction. 8vo. 420 pp. *London*, 1922

Chalkley, A. P. Diesel engines for land and marine work. With an introductory chapter by Dr. R. Diesel. 5th ed. 8vo. 347 pp. *London*, 1922

Conjoint Board of Scientific Societies, The. Water-power in the British Empire: The Reports of the Water-Power Committee of the C.B. of S.S. Sir Dugald Clerk, K.B.E., F.R.S. (Chairman); Prof. A. H. Gibson, D.Sc. (Secretary). sm. 8vo. 63 pp. *London*, 1922

Constantinesco, G. Theory of wave transmission. A treatise on transmission of power by vibrations. 2nd ed. 8vo. 213 pp. *London*, 1922

Coursey, P. R. The wireless telephone. What it is, and how it works. sm. 8vo. 112 pp. *London*, 1922

Davidge, H. T., and Hutchinson, R. W. Technical electricity. 4th ed. 8vo. 526 pp. *London*, 1922

Department of Scientific and Industrial Research. Report of the Fuel Research Board for the years 1920, 1921. Second section: Low temperature carbonisation. 8vo. 73 pp. 8 pl. *London*, 1922

Dover, A. T. Industrial motor control. Direct current. sm. 8vo. 128 pp. *London*, 1922

East Africa Protectorate. An Ordinance to make provision for the generation, transmission, delivery, sale, purchase, and use of electrical energy; and for the making and enforcing of regulations appertaining to and governing such purposes; and for the provision and enforcing of penalties for any contravention of this Ordinance or of the regulations made under it. folio. 94 pp. *Nairobi*, 1920

Electrical Power Engineers' Association. Report on the training of electrical power engineers.
8vo. 18 pp. *London*, 1922

Findlay, A. The treasures of coal tar.
sm. 8vo. 151 pp. *London*, 1917

Flight, W. S. Phenol-formaldehyde products in the electrical industry. The effect of heat on the electric strength of some commercial insulating materials. Machining ebonite, fibre, and other insulating materials [*anonymous*].
8vo. 72 pp. *Preston, n.d.*

Garcke, E., and Fells, J. M. Factory accounts, in principle and practice. 7th ed., revised, with a foreword by J. M. Fells. 8vo. 310 pp. *London*, 1923

Gibson, A. H., *D.Sc., editor*. Hydro-electric engineering. vol. 2, Electrical. Contributors: W. A. Coates, F. E. Hill, S. Neville, and the editor.
la. 8vo. 321 pp. *London*, 1922

Glazebrook, *Sir* R., *K.C.B., D.Sc.* A dictionary of applied physics. vol. 1, 2. 8vo. *London*, 1922

1, Mechanics—Engineering—Heat.
2, Electricity.

Goudie, W. J., *D.Sc.* Steam turbines. 2nd ed.
8vo. 822 pp. *London*, 1922

Haler, P. J., and Stuart, A. H. A second course in engineering science.
sm. 8vo. 257 pp. *London*, 1922

Hawkins, C. C. The dynamo: its theory, design and manufacture. 6th ed. vol. 1.
8vo. 638 pp. *London*, 1922

*The earlier editions of this work are by C. C. Hawkins and F. Wallis.*

India: Punjab Public Works Department. The Sutlej River Hydro-Electric Scheme. By Bt. Lieut.-Col. B. C. Battye.
vol. A, 5–8. folio. *Lahore*, 1921–22

Keen, R. Direction and position finding by wireless.
8vo. 376 pp. *London*, 1922

Keinath, G. Die Technik der elektrischen Messgeräte.
8vo. 455 pp. *München*, 1921

Kemp, P. Alternating current electrical engineering. [2nd ed.] 8vo. 526 pp. *London*, 1922

Langman, H. R., and Ball, A. Electrical horology. A practical manual on the application of the principles and practice of electricity to horological instruments and machines for the measurement and transmission of time; with an account of the earliest electrically-driven clock mechanism.
sm. 8vo. 175 pp. *London*, 1923

London County Council. Reports on the manufacture of gauges and the training of munition workers in certain London technical institutions during the war. 8vo. 90 pp. *London*, 1921

Main, F. W. Electric cables.
sm. 8vo. 111 pp. *London*, 1922

Marsh, C. F., and Dunn, W. Manual of reinforced concrete. sm. 8vo. 520 pp. *London*, 1922

Marshall, C. W. Modern central stations.
sm. 8vo. 125 pp. *London*, 1921

Meares, J. W., *C.I.E.* The law relating to electrical energy in India. 2nd ed., revised.
8vo. 403 pp. *Calcutta*, 1922

Molesworth, *Sir* G. L. Life of Sir G. L. Molesworth, K.C.I.E. "The Nestor of the engineering profession." Edited by W. J. Molesworth.
8vo. 224 pp. *London*, 1922

Mottelay, P. F., *Ph.D.* Bibliographical history of electricity and magnetism, chronologically arranged. Researches into the domain of the early sciences, especially from the period of the revival of scholasticism, with biographical and other accounts of the most distinguished natural philosophers throughout the middle ages. With an introduction by the late Prof. S. P. Thompson, D.Sc., F.R.S., and a foreword by Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S.
la. 8vo. 693 pp. *London*, 1922

Murray, *River*. Harnessing Australia's greatest river: being an account of the great scheme undertaken by the governments of the Commonwealth of Australia, and of the States of New South Wales, Victoria, and South Australia, with a view to the more profitable use of the waters of the River Murray, etc. [Supplement to "The Industrial Australian and Mining Standard," 17th June, 1920.]
folio. 51 pp. *Melbourne*, 1920

Oulton, L., and Wilson, N. J. Practical testing of electrical machines. [2nd ed.]
sm. 8vo. 258 pp. *London*, 1921

Parr, G. D. A. Electrical engineering testing. A practical work on continuous and alternating currents for second and third year students and engineers. 4th ed. 8vo. 703 pp. *London*, 1922

Poole, H. E. Switching and switchgear.
sm. 8vo. 127 pp. *London*, 1922

Practical Engineer, The, electrical pocket book and diary for 1923 (with buyers' guide and technical dictionaries in French, Spanish, and Russian). 24th year of issue. Edited by C. Arnold.
sm. 8vo. 760 pp. *London*, [1922]

Price, H. W., and Duff, C. K. Papers on current transformers. [University of Toronto, School of Engineering Research, Bulletin No. 2, 1921.]
8vo. 65 pp. *Toronto*, 1921

Radio Instruments, Ltd. Working diagrams of valve receiving circuits.
sm. obl. 8vo. 21 diagrams. *London*, [1922]

Roget, S. R. A first book of applied electricity.
sm. 8vo. 150 pp. *London*, 1921

Smith, C. F. The testing of transformers and alternating current machines.
sm. 8vo. 102 pp. *London*, 1922

Spiegelhalter, E. K. Wireless valve receiver set. How to make it.
sm. 8vo. 79 pp. *London*, 1922

Summers, A. L. Anthracite and the anthracite industry. sm. 8vo. 135 pp. *London*, [1922]

Taylor, W. T. Electric power systems.
sm. 8vo. 119 pp. *London*, 1922

—— High voltage power transformers.
sm. 8vo. 127 pp. *London*, 1922

Thomas, H. Traité de télégraphie électrique. 2e éd.
la. 8vo. 1 224 pp. *Paris*, 1922

UNITED STATES. ARMY: SIGNAL CORPS. The principles underlying radio communication. 2nd ed. Radio communication pamphlet no. 40. Revised to May 24, 1921.
sm. 8vo. 619 pp. *Washington*, 1922

VICTORIA, *State*. "Power" for Victorian industries A complete account of the great electric power and fuel supply scheme authorised by the Premier (Mr. H. S. Lawson) and State Government of Victoria, and now being carried into effect by the Victorian Electricity Commissioners; etc. [Supplement to "The Industrial Australian and Mining Standard," 17th March, 1921.]
folio. 79 pp. *Melbourne*, 1921

WADDELL, J. A. L. Specifications and contracts. A series of lectures; including examples for practice in specification and contract writing, together with notes on the Law of Contracts.
8vo. 169 pp. *New York*, 1922

—— Two addresses to the engineering students of the University of Barcelona. Delivered April 19th and 21st, 1922.
8vo. 23 pp. [*New York*, 1922]

WALMSLEY, R. M., *D.Sc.* Electricity in the service of man. vol. 2, section iii, Technology of electricity.
8vo. 863 pp. *London*, 1921

WAR OFFICE. Signals Experimental Establishment. Technical report. September, 1922. [*In MS.*]
fol. [*Woolwich*, 1922]

WESTERN AUSTRALIA. Electricity supply stations of W.A., 1922. Compiled by A. F. Williamson.
obl. folio sheet. *Perth*, 1922

WHITE, H. G. Telephone erection and maintenance. 3rd ed. sm. 8vo. 151 pp. *London*, [1922]

WHITE, W. J. Questions and solutions in magnetism and electricity. Consisting of solutions to the questions set by the Board of Education and City and Guilds of London Institute in stage 1 of magnetism and electricity during the years 1907–1921. Solutions by W. J. W. [2nd ed.]
sm. 8vo. 107 pp. *London* [1921]

WHO'S WHO IN ENGINEERING. Directory and manual. Ed. by J. E. Sears, junr. 3rd ed.
la. 8vo. 1211 pp. *London*, 1923

WHYTE, A. G. The all-electric age.
8vo. 255 pp. *London*, 1922

WIMPERIS, H. E. The internal combustion engine. 4th ed., revised. 8vo. 336 pp. *London*, 1922

YATES, R. F., and PACENT, L. G. The complete radio book. Preface by A. A. C. Swinton, F.R.S.
8vo. 343 pp. *London*, 1922

YOUNG, A. P., and WARREN, H. Sparking plugs.
sm. 8vo. 119 pp. *London*, 1922

# THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 38. MAY 1923. INSTITUTION NOTES. [ISSUED WITH No. 318 OF THE JOURNAL.

## Annual General Meeting.

The 51st Annual General Meeting of the Institution (Corporate Members and Associates only) will be held on Thursday, 31st May, 1923, at 6 p.m.

## Annual Conversazione.

The Annual Conversazione will be held at the Natural History Museum, South Kensington, by permission of the Trustees of the Museum, on Thursday, 28th June, 1923.

## The Institution of Engineers (India).

The I.E.E. Premium, value £20 (see *Institution Notes*, No. 16, page 2, December 1919), has been awarded by the Council of the above Institution for the year ended 31st August, 1922, to Mr. A. Lennox Stanton for his paper on "Railway Electrification, with special reference to Indian Conditions."

## Associate Membership Examination Results.

### OCTOBER 1922, SUPPLEMENTARY LIST.*

*Passed.*

Plowman, A. S. . . . (Sydney, Australia).

### FEBRUARY 1923, ROYAL CORPS OF SIGNALS.

*Passed.*

Bennett, M. C., Lieutenant (Indian Army).
Boyd, L. C., Lieutenant (Royal Ulster Rifles).
Boyt, W. D., Lieutenant (Royal Garrison Artillery).
Crouch, C. H., Lieutenant (Royal Garrison Artillery).
Halliday, G. R., Lieutenant (Royal Garrison Artillery).
Hannah, A. J., Captain (Indian Army).
Helps, R. P. A., O.B.E., M.C., Captain (Lancashire Fusiliers).
Hemming, W. E. G., Lieutenant (Royal Garrison Artillery).
Holland, V. C., Lieutenant (Royal Artillery).
Howard-Smith, M. H., Captain (Indian Army).
Instrall, R. C., Lieutenant (Royal Garrison Artillery).
Neale, R. H., Captain (Lincolnshire Regiment).
Plummer, G. H., Lieutenant (Cameronians).
Stoddart, E., Lieutenant (Royal Garrison Artillery).
Thomas, W. F. P., Lieutenant (South Staffordshire Regiment).
Watkins, B. S., Lieutenant (Indian Army).

## International Consulting Committee for International Telephone Communication.

As a result of the suggestions made in the President's Inaugural Address delivered before the Institution on the 2nd November last, M. Paul Laffont, Sous-Secrétair de l'Administration des Postes et des Télégraphes for France, called a preliminary technical international conference to study and recommend what steps should be taken by the European Administrations to improve and consolidate international telephone traffic in Europe.

The meeting was held in Paris commencing on 12th March, 1923, and was presided over by Monsieur Dennery, Inspecteur-Général des Postes et des Télégraphes, and was attended by representatives from France, Belgium, Great Britain, Italy, Spain, and Switzerland. The deputation for Great Britain was headed by Major T. F. Purves, O.B.E., Engineer-in-Chief to the British Post Office, and the other nations were similarly strongly represented.

At this conference certain recommendations were decided upon and these will, in due course, be submitted to the various Administrations in Europe. In the meantime, it may be stated that the committee has emphasized, as of primary importance, the necessity of complete unity as regards principles and practical realization—under present conditions of the telephone art—as well as in all matters concerning material and technical and commercial operation.

Consequently the committee has recognized the necessity for forming a permanent international consulting commission for international telephone communications. The different countries of Europe will be represented on this Commission, the official title of which will be Comité Consultatif International des Communications Téléphoniques Internationales.

The continuity of the work of this Commission will be secured by the establishment of a permanent Secretariat in Paris, which will also be a centre for international technical information. Pending the constitution of the Comité Consultatif International, the preliminary technical Committee has decided that its President, M. Dennery, and its General Secretary, M. Valensi, shall fill provisionally the offices of President and of permanent Secretary of the Comité Consultatif International.

The preliminary technical Committee has indicated the guiding principles, from now onwards, for the construction of international lines, their maintenance and development.

The collaboration between nations created by this preliminary Committee has permitted, moreover, the formulation of a programme for new routes of communication both by aerial lines and by cables which are immediately required and which should be completed in 1923 and 1924. Finally the Committee will prepare a decennial programme for European telephone trunk lines. The main outlines of the scheme have already been determined and it will be completed during the course of the year.

---

* See *Institution Notes*, No. 35, page 1, December 1922, and No. 37, page 9, March 1923.

## Informal Meetings.

The following Informal Meetings have been held :—

### 38th Informal Meeting (22nd January, 1923).

*Chairman :* Mr. A. B. Eason.

*Subject of Discussion :* "Insulators and Insulating Materials" (introduced by Mr. A. G. Warren).

*Speakers :* Messrs. E. W. Moss, C. C. Paterson, O.B.E., H. M. Sayers, W. E. Rogers, A. C. Warren, E. H. Rayner, W. S. Flight, A. Monkhouse, A. Rosen, A. Collins and P. Dunsheath.

### 39th Informal Meeting (5th February, 1923).

*Chairman :* Mr. F. Pooley.

*Subject of Discussion :* "The Supply of Steady D.C. for Telephonic and other Purposes" (introduced by Mr. J. Coxon).

*Speakers :* Messrs. F. Reid, A. F. Harmer, W. E. Rogers, C. J. Ashton, R. J. Hines, H. J. Gregory, F. W. Adcock, H. Kingsbury, A. B. Eason, W. L. Wreford, J. R. Bedford, R. V. Hook, G. H. Elsden and F. Pooley.

### 40th Informal Meeting (19th February, 1923).

*Chairman :* Mr. E. F. Hetherington.

*Subject of Discussion :* "Esprit de Corps" (introduced by Mr. F. Peake Sexton).

*Speakers :* Major G. H. Spittle, D.S.O., Messrs. W. E. Rogers, J. R. Bedford, F. Pooley, W. Lunn, E. F. Hetherington, A. G. Hilling, H. H. Long, J. Coxon, M. Whitgift and W. L. Wreford.

### 41st Informal Meeting (5th March, 1923).

*Chairman :* Mr. A. F. Harmer.

*Subject of Discussion :* "Control in Industry" (introduced by Mr. J. H. Parker).

*Speakers :* Messrs. W. Day, N. Wylde, H. W. Healey, W. E. Warrilow, W. E. Rogers, F. C. Knowles, W. J. Oswald, — Bing, G. J. D. Scott, A. G. Whyte and A. H. Bennett.

### 42nd Informal Meeting (19th March, 1923).

*Chairman :* Mr. W. E. Warrilow.

*Subject of Discussion :* "The Need for Co-operation between Electrical Manufacturers and Contractors" (introduced by Messrs. H. T. Young and J. F. Caine).

*Speakers :* Messrs. E. E. Sharp, W. R. Rawlings, A. G. Beaver, W. Day, A. F. Harmer, W. E. Rogers, C. Peel, A. Windibank, E. C. Wansbrough, F. Gill, E. H. Marryat, A. Wise, G. J. D. Scott and Major H. Brown.

### 43rd Informal Meeting (23rd April, 1923).

*Chairman :* Mr. E. W. Moss.

*Subject of Discussion :* "Practical Broadcasting" (introduced by Mr. E. H. Shaughnessy, O.B.E.).

*Speakers :* Captain P. P. Eckersley, Messrs. J. Scott-Taggart, J. R. Bedford, W. L. Wreford, R. Grierson, G. D. Dewar, W. E. Rogers, P. R. Coursey, W. Day, E. G. Bedford, A. C. Warren, A. G. Lee, H. S. Pocock, E. F. Hetherington, W. E. Warrilow, W. H. Lawes, E. W. Moss and J. C. W. Reith.

## National Illumination Committee of Great Britain.*

### REPORT OF CHAIRMAN FOR YEAR 1922.

In February last (1922) the provisional Definitions of Photometric Terms and Units proposed by the British National Committee were published together with a prefatory note and have been officially adopted by the three constituent Societies. They also form the basis of a set of Photometric Definitions shortly to be issued by the British Engineering Standards Association as part of a comprehensive set of Electrical Engineering terms.

The Definitions in question, whilst agreeing with the decisions of the International Commission on Illumination held in Paris in 1921, go considerably further and are in some respects at variance with a set of Definitions approved in July, 1922, by the American Engineering Standards Committee. The occasion of a visit by Dr. Clayton Sharp to this country in December last was seized upon to discuss these Definitions with one so largely instrumental in the drafting of the American Definitions. Dr. Sharp kindly consented to attend a Meeting of the Nomenclature Sub-Committee, and as a result of this interchange of views, the Sub-Committee are now considering how the proposed Definitions can be amended so as to minimize the points of difference between this country and the United States.

A preliminary list of Symbols has also been prepared by the Nomenclature Sub-Committee and, after submission to the British Committee, these have been communicated to a number of interested Societies, publication being deferred until their criticisms, if any, have been considered.

Dr. Mailloux (U.S.A.) and Mr. K. Edgcumbe (Gt. Britain) were asked by the central office of the National Illumination Commission to prepare an English translation of the French official text of Terms and Definitions adopted in Paris in 1921. A Meeting was held in this country and the translation agreed upon. The text forms an Appendix to this Report.

At the 1921 Paris Meeting of the Commission an International Committee on Automobile Headlights was appointed and Mr. K. Edgcumbe was subsequently nominated by the British National Committee as their Representative thereon. A fairly complete set of recommendations having been drawn up in the United States by a Committee under the Chairmanship of Dr. Clayton Sharp, the subject was discussed with that gentleman on the occasion of his visit to this country, and at a subsequent interview with Mr. Perrin of the Ministry of Transport the question was raised of how the British National Committee could best serve the interests of this country in connection with Automobile Headlights. It appeared that the most useful course would be to appoint a Sub-Committee to consider the recommendations which had already been published in other countries, with a view, if possible, of arriving at common agreement through the medium of the International Headlights Committee.

---

* See *Institution Notes*, No. 30, page 11, January 1922.

In view of the fact that a large and increasing part of the work of the British National Committee relates to standardization, it was decided, with the approval of the three constituent Societies, to ask the British Engineering Standards Association to form a sectional Committee on Illumination to which such matters could be referred. It is proposed that this Committee should deal solely with standardization or similar questions referred to it by the British National Committee, all international matters being dealt with by the National Committee as heretofore.

K. Edgcumbe.
*Chairman.*

*January*, 1923.

## PHOTOMETRIC DEFINITIONS.

### Official Translation of the French Text.

*Luminous flux.*—Is the rate of passage of radiant energy evaluated by reference to the luminous sensation produced by it.

Although luminous flux should be regarded, strictly, as the rate of passage of radiant energy as just defined, it can, nevertheless, be accepted as an entity for the purposes of practical photometry, since the velocity may be regarded as being constant under those conditions.

*The unit of luminous flux is the lumen.*—It is equal to the flux emitted in unit solid angle by a uniform point source of one international candle.

*Illumination.*—The illumination at a point of a surface is the density of the luminous flux at that point, or the quotient of the flux by the area of the surface when the latter is uniformly illuminated.

*The practical unit of illumination is the lux.*—It is the illumination of a surface one square metre in area, receiving a uniformly distributed flux of one lumen, or the illumination produced at the surface of a sphere having a radius of one metre by a uniform point source of one international candle situated at its centre.

In view of certain recognized usages, illumination may also be expressed in terms of the following units :—

Taking the centimetre as the unit of length, the unit of illumination is the lumen per square centimetre ; it is known as the "phot." Taking the foot as the unit of length, the unit of illumination is the lumen per square foot ; it is known as the "foot-candle."

$$\begin{aligned}1 \text{ foot-candle} &= 10{\cdot}764 \text{ lux}\\ &= 1{\cdot}0764 \text{ milli-phot}\end{aligned}$$

*Luminous intensity (candle-power).*—The luminous intensity (candle-power) of a point source in any direction is the luminous flux per unit solid angle emitted by that source in that direction. (The flux emanating from a source whose dimensions are negligible in comparison with the distance from which it is observed may be considered as coming from a point.)

*The unit of luminous intensity (candle-power)* is the International Candle, such as resulted from agreements effected between the three National Standardizing Laboratories of France, Great Britain and the United States, in 1909.*

This unit has been maintained since then by means of incandescent electric lamps in these laboratories which continue to be entrusted with its maintenance.

## Accessions to the Lending Library.

Bowker, W. R. Electrical circuits and connections. A technical, practical, and operative treatise on direct, alternating, polyphase, and hydro-electrical engineering circuits. Being the 3rd enlarged edition of "Dynamo, motor and switchboard circuits." 8vo. 223 pp. *London*, 1922

Chilton, F. E. Electric cranes and hauling machines. sm. 8vo. 124 pp. *London*, 1923

Collins, A. F. The radio amateur's handbook. 8vo. 348 pp. *London*, 1922

Coursey, P. R. The radio experimenter's handbook. pt. 2, Data and design. 8vo. 78 pp. *London*, 1923

Cross, H. H. U. Electric lighting and starting for motor cars. 8vo. 340 pp. *London*, 1923

Eason, A. B. The prevention of vibration and noise. 8vo. 175 pp. *London*, [1923]

Fleming, J. A., *D.Sc.*, *F.R.S.* Electrons, electric waves and wireless telephony. Being a reproduction with some amplification of the Christmas Lectures delivered at the Royal Institution of Great Britain, December, 1921, January, 1922. sm 8vo. 334 pp. *London*, [1923]

Harrison, H. H. Printing telegraph systems and mechanisms. 8vo. 447 pp. *London*, 1923

Hawkhead, J. C. Handbook of technical instruction for wireless telegraphists. 2nd ed., extensively revised and enlarged by H. M. Dowsett. 8vo. 325 pp. *London*, 1915

Hawkins, C. C. The dynamo : its theory, design and manufacture. 6th ed. vol. 2 (Continuous-current dynamos). 8vo. 338 pp. *London*, 1923

---

* These Laboratories are: the Laboratoire Central d'Electricité in Paris; the National Physical Laboratory in Teddington, and the Bureau of Standards in Washington.

Hobart, H. M. Electric motors; their theory and construction. 3rd ed. vol. 1, Chiefly concerning direct current. 8vo. 428 pp. *London*, 1923

Kaye, G. W. C., *O.B.E.*, *D.Sc.* The practical applications of x-rays. 8vo. 143 pp. *London*, 1922

Lamme, B. G. Electrical engineering papers. 8vo. 773 pp. *East Pittsburgh, Pa.*, 1919

Langman, H. R., and Ball, A. Electrical horology. A practical manual on the application of the principles and practice of electricity to horological instruments and machines for the measurement and transmission of time. With an account of the earliest electrically-driven clock mechanism. sm. 8vo. 175 pp. *London*, 1923

Low, D. A. Heat engines, embracing the theory, construction, and performance of steam boilers, reciprocating steam engines, steam turbines and internal combustion engines. A text-book for engineering students. 8vo. 599 pp. *London*, 1922

Parr, G. D. A. Electrical engineering testing; a practical work on continuous and alternating currents for second and third year students and engineers. 4th ed. 8vo. 703 pp. *London*, 1922

Rose, W. N. Line charts for engines. 8vo. 107 pp. *London*, 1923

Stanley, R. Text-book on wireless telegraphy. vol. 2, Valves and valve apparatus. 2nd ed. 8vo. 405 pp. *London*, 1923

Taylor-Jones, E., *D.Sc.* The theory of the induction coil. 8vo. 228 pp. *London*, 1921

Thompson, W. P. Handbook of patent law of all countries. 18th ed. 8vo. 164 pp. *London*, 1920

Yates, R. F., and Pacent, L. G. The complete radio book. Preface by A. A. Campbell Swinton, F.R.S. 8vo. 343 pp. *London*, 1922

## Accessions to the Reference Library.

Allsop, F. C. Practical electric-light fitting. A treatise on the wiring and fitting-up of buildings deriving current from central station mains, and the laying down of private installations. 9th ed. sm. 8vo. 295 pp. *London*, 1923

Beauchamp, J. W. Industrial electric heating. sm. 8vo. 128 pp. *London*, 1923

Blattner, E. Lehrbuch der Elektrotechnik. 4e Aufl. Teil 1. 8vo. 432 pp. *Bern*, 1922

California: Railroad Commission of the State of California. Inductive interference between electric power and communication circuits. Selected technical reports with preliminary and final reports of the Joint Committee on Inductive Interference and Commission's General order for prevention or mitigation of such interference. April 1, 1919. 8vo. 1 160 pp. *Sacramento*, 1919

Chilton, F. E. Electric cranes and hauling machines. sm. 8vo. 124 pp. *London*, 1923

Erskine-Murray, J. Wireless telephones, and how they work. 3rd ed. 84 pp. *London*, 1923

Fleming, J. A., *D.Sc.*, *F.R.S.* Electrons, electric waves and wireless telephony. Being a reproduction with some amplification of the Christmas Lectures delivered at The Royal Institution of Gt. Britain, Dec., 1921, Jan., 1922. sm. 8vo. 334 pp. *London*, [1923]

—— The principles of electric wave telegraphy and telephony. 4th ed. 8vo. 722 pp. *London*, 1919

Glazebrook, *Sir* R., *K.C.B.*, *D.Sc.* A dictionary of applied physics. vol. 3, 4. 8vo. *London*, 1923

3, Meteorology—Metrology and Measuring apparatus.
4, Light—Sound—Radiology.

Gordon, J. W. Generalised linear perspective, treated with special reference to photographic land surveying and military reconnaissance. 8vo. 200 pp. *London*, 1922

Harrison, H. H. Printing telegraph systems and mechanisms. 8vo. 447 pp. *London*, 1923

Haynes, F. H. The amateurs' book of wireless circuits. obl. 8vo. 107 pp. *London*, 1923

Institution of Engineers, The, Australia. Transactions, vol. 1, 1920. 8vo. 480 pp. *Sydney*, 1921

Johnson, B. K. Practical optics for the laboratory and workshop. With a foreword by Prof. [F. J.] Cheshire, C.B.E. 8vo. 189 pp. *London*, 1922

Lertes, P. Die drahtlose Telegraphie und Telephonie. 8vo. 163 pp. *Dresden*, 1922

Marec, E. La force motrice électrique dans l'industrie. Avec une préface de P. Janet. 8vo. 621 pp. *Paris*, 1922

Pender, H. Direct-current machinery. A text-book on the theory and performance of generators and motors. 8vo. 324 pp. *New York*, 1922

Scott-Maxwell, J. M. Costing and price-fixing. With a foreword by Lord Weir. 8vo. 223 pp. *London*, 1923

Standard handbook for electrical engineers. Prepared by a staff of specialists. F. F. Fowle, editor-in-chief. 5th ed. sm. 8vo. 2 155 pp. *New York*, 1922

Union des Syndicats de l'Electricité. Construction & exploitation des grands réseaux de transport d'énergie électrique a très haute tension. Compte-rendu des travaux de la Conférence Internationale tenue à Paris du 21 au 26 novembre, 1921. Etabli par J. Tribot Laspière. 8vo. 1 176 pp. *Paris*, 1922

Yorke, J. P. Magnetism & electricity. new ed. 8vo. 256 pp. *London*, 1922

# THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 39. July 1923.

## INSTITUTION NOTES.

[Issued with No. 320 of the Journal.]

### Council for the Year 1923–24.

The scrutineers appointed at the Ordinary Meeting on the 10th May, 1923, in connection with the ballot to fill the vacancies which will occur in the Council on the 30th September next, have reported to the President the result of the ballot as follows :—

*President :* Dr. A. Russell.
*Vice-President :* Sir James Devonshire, K.B.E.
*Hon. Treasurer :* Mr. P. D. Tuckett.
*Ordinary Members of Council :* (Members) Captain J. M. Donaldson, M.C., Mr. G. W. Partridge, Colonel T. F. Purves, O.B.E., Mr. P. Rosling and Professor W. M. Thornton, O.B.E., D.Sc. ; (Associate Member) Mr. S. W. Melsom.

The Council for the year 1923–24 will therefore be constituted as follows :—

#### President.

A. Russell, M.A., D.Sc.

#### The Past-Presidents.

#### Vice-Presidents.

Sir James Devonshire, K.B.E.
Prof. E. W. Marchant, D.Sc.
C. C. Paterson, O.B.E.
A. A. C. Swinton, F.R.S.

#### Honorary Treasurer.

P. D. Tuckett.

#### Ordinary Members of Council.

J. W. Beauchamp.
R. A. Chattock.
F. W. Crawter.
Captain J. M. Donaldson, M.C.
D. N. Dunlop.
K. Edgcumbe.
S. Evershed.
A. F. Harmer.
Lt.-Col. F. A. Cortez Leigh, T.D., R.E.
S. W. Melsom.
Sir Andrew M. Ogilvie, K.B.E., C.B.
A. Page.
G. W. Partridge.
Col. T. F. Purves, O.B.E.
W. R. Rawlings.
T. Roles.
P. Rosling.
Prof. W. M. Thornton, O.B.E., D.Sc.

and

The Chairman and immediate Past-Chairman of each Local Centre.

### List of Members.

A new List of Members is in preparation and will be ready in the autumn. Members wishing to receive a copy are requested to make early application to the Secretary.

### Ten-Year Index.

A Ten-Year Index to Volumes 48 to 59 (years 1912–1921) of the *Journal* will shortly be ready. The published price is 10s. 6d. per copy, but members (of any class) of the Institution who have not already filled in an order form may obtain copies at the reduced rate of 2s. 6d. each post free by ordering copies without delay. Orders should be sent to the Secretary of the Institution, Savoy Place, Victoria Embankment, London, W.C. 2.

### Annual Subscriptions.

At the recent Annual General Meeting the President announced that the Council had, under the provisions of Bye-Law 27, reduced the subscriptions of Corporate Members by 10s. and those of Graduates by 5s. as from the 1st January, 1924. From that date the subscriptions will accordingly be as follows :—

| | In Great Britain, Ireland, the Isle of Man and the Channel Islands. | | | Abroad. | | |
|---|---|---|---|---|---|---|
| | £ | s. | d. | £ | s. | d. |
| Members .. .. .. .. | 4 | 15 | 0 | 3 | 15 | 0 |
| Associate Members .. .. | 3 | 5 | 0 | 2 | 15 | 0 |
| Associates .. .. .. .. | 4 | 5 | 0 | 3 | 15 | 0 |
| Graduates .. .. .. .. | 2 | 5 | 0 | 2 | 5 | 0 |
| Students, until the end of the calendar year in which the age of 21 is attained .. .. | 1 | 1 | 0 | 1 | 1 | 0 |
| Students, after the calendar year in which the age of 21 is attained | 1 | 11 | 6 | 1 | 11 | 6 |

The subscription to *Science Abstracts* is as follows :—

| | s. | d. | |
|---|---|---|---|
| Section A (Physics) .. .. .. | 12 | 6 | per annum |
| Section B (Electrical Engineering) .. | 12 | 6 | per annum |
| Both Sections .. .. .. | 20 | 0 | per annum |

The above are specially reduced rates for members of the Institution, the subscription payable by the general public being 30s. for either Section alone, or 50s. for the two.

A prospectus of the publication, with specimen abstracts, can be obtained from the Secretary.

## Short Papers for Journal.

The Papers Committee would like it generally known that short papers and notes on novel features in electrical engineering or in science applied thereto are acceptable for publication in the *Journal*. Contributions need not be confined to the handling of complete subjects by means of long papers. Recent advances or discoveries for which members are responsible, even though of limited scope or application, are often worthy of publication in the form of concisely written articles.

## Premiums.

At the Annual General Meeting held on 31st May, 1923, the President announced that the Council had awarded the following premiums for papers :—

*The Institution Premium (value £25).*

| | |
|---|---|
| The late Dr. G. Kapp. | "The Improvement of Power Factor." |

*The Ayrton Premium (value £10).*

| | |
|---|---|
| F. Creedy. | "Variable-Speed Alternating-Current Motors without Commutators." |

*The Fahie Premium (value £10).*

| | |
|---|---|
| Dr. H. W. Nichols. | "Transoceanic Wireless Telephony." |

*The John Hopkinson Premium (value £10).*

| | |
|---|---|
| J. Rosen. | "Some Problems in High-Speed Alternators, and their Solution." |

*The Kelvin Premium (value £10).*

| | |
|---|---|
| S. W. Melsom and H. C. Booth. | "The Efficiency of Overlapping Joints in Copper and Aluminium Busbar Conductors" and "The Rating of Cables for Intermittent or Fluctuating Loads." |

*The Paris Premium (value £10).*

| | |
|---|---|
| J. Caldwell. | "Electric Arc Welding Apparatus and Equipment." |

*Extra Premiums (value £5 each).*

| | |
|---|---|
| L. Breach and H. Midgley. | "The Drive of Power Station Auxiliaries." |
| F. T. Chapman, D.Sc. | "The Production of Noise and Vibration by Certain Squirrel-Cage Induction Motors." |
| A. T. Dover. | "A Universal 'Chart' Method of Calculating Starting Rheostats for Direct-Current Motors." |
| P. J. Robinson. | "The Maintenance of Voltage on a D.C. Distribution System by Means of a Fully Automatic Substation." |

### Wireless Section Premiums.

*A Premium (value £10).*

| | |
|---|---|
| N. W. McLachlan, D.Sc. | "The Application of a Revolving Magnetic Drum to Electric Relays, Siphon Recorders and Radio Transmitting Keys." |

*A Premium (value £10).*

| | |
|---|---|
| E. B. Moullin, M.A. | "A Direct-reading Thermionic Voltmeter, and its Applications." |

*Extra Premium (value £5).*

| | |
|---|---|
| Prof. C. L. Fortescue. | "The Design of Inductances for High-Frequency Circuits." |

*Extra Premium (value £5).*

| | |
|---|---|
| J. Hollingworth, M.A., B.Sc. | "The Measurement of the Electric Intensity of Received Radio Signals." |

The Premiums for papers read before the Students' Sections will be announced later.

## Portrait of Sir Francis Ronalds.

Mrs. Ortmans, a great-niece of Sir Francis Ronalds, has presented to the Institution a painting of Sir Francis at work on the catalogue of the Ronalds Library, of which the Institution has the custody.

## National Certificates and Diplomas in Electrical Engineering.

The following Schools and Colleges have recently been approved under the scheme drawn up jointly by the Board of Education and the Institution for the purpose of awarding the above Certificates and Diplomas to students who successfully complete approved courses and pass the prescribed examinations.

Further lists of approved Schools will be published from time to time.

*Approved for Ordinary Grade Certificates. (Senior Part-Time Courses.)*

Blackburn Municipal Technical College.
Blackpool Technical College.
Bolton Municipal Technical School.
Lancaster—Storey Institute.
Leigh (Lancs) Technical School.
London—The Polytechnic, Regent Street.
Loughborough College.
Rugby Technical School.
St. Helens Municipal Technical School.
Stafford Technical School.
Widnes Municipal Technical School.

*Approved for Higher Grade Certificates. (Advanced Part-Time Courses.)*

Rugby Technical School.

## Associate Membership Examination Results.

### April 1923.

*Passed.*

Aylott, H. J.
Ball, E. T. R.
Banks, W. Q.
Base, G. C.
Bearman, C. W. G.
Beaumont, F. N.
Currah, L. E.
Daniel, C. R.
Dean, A. R.
Denman, R. P. G.
Dunn, E. E.
Edwards, L.
Favell, F.
Featherstone, H.
Harris, C. E.
Hinds, G. A. R.
Hollis, A. C.
Hulcoop, F. A.
Johnson, C. V.
Johnson, C. W.
Kearley, N. E.
Kingaby, G. W.
McCulloch, R. A.
Mendelson, J.
Minton, W. J.
Morris, C. I.
Pilgrim, W. H.
Pollard, A. H.
Reed, F. R.
Ross, E. G.
Rowland, F. E.
Sadler, E. H.
Sennett, H. H.
Sims, R. J.
Thompson, H. E.
Tucker, J. P.
Wade-Cooper, F.
Waggott, H. C.
Watton, E. B.
Watts, D.
Weare, H. O.
Wilman, C. W.

*Passed Part I only.*

Bellamy-Law, J. W.
Dell, R.
Kitto, F. M.
Rayner, F. J.

*Passed Part II only.*

Bailey, G. S.
Bleasdale, J. W.
Bradford, P. J.
France, W. G.
Galliard, J. D.
Harris, G. S.
Irwin, A. E.
Price, S. C.
Rea, J. R.
Stinchcomb, E. A.

### Officers of the Corps of Royal Engineers.

*Passed.*

Ahern, Lieut. P. J.
Bagnall-Wild, 2nd Lieut. R. E.
Bishop, 2nd Lieut. R. A.
Blenkinsop, 2nd Lieut. R. I. C.
Blundell, 2nd Lieut. J. H.
Blunt, 2nd Lieut. D. S.
Boulden, 2nd Lieut. C. B.
Bradshaw, 2nd Lieut. F. C. C.
Bryan, 2nd Lieut. G. J.
Burn, 2nd Lieut. D. M.
Cadell, 2nd Lieut. I. M.
Cam, Captain G.
Cran, 2nd Lieut. F. K.
Deane, 2nd Lieut. D. V.
de Brett, 2nd Lieut. E. S.
Dove, 2nd Lieut. A. J. H.
Fenwick, 2nd Lieut. D. H.
Gordon, 2nd Lieut. G. A.
Green, 2nd Lieut. F. M.
Highway, Lieut. F. T. G.
Howe, 2nd Lieut. J. S.
Hutchins, 2nd Lieut. H. R. P.
Landor, 2nd Lieut. J. W. N.
Lendrum, 2nd Lieut. H. L.
Loftus-Tottenham, 2nd Lieut, H. T. L.
Maconochie, 2nd Lieut. D.
May, 2nd Lieut. N. E.
Michelli, Captain P. F. M.
Micklam, 2nd Lieut. G. V.
Owen, 2nd Lieut. J. R. L.
Parker, 2nd Lieut. C. G. W.
Pritchard, 2nd Lieut. G. A. T.
Reilly, 2nd Lieut. J. F. C.
Richardson, 2nd Lieut. G. N.
Scratchley, 2nd Lieut. P. J.
Seagrim, 2nd Lieut. C. V.
Stileman, 2nd Lieut. E. C. R.
Swales, 2nd Lieut. N. R.
Vaughan-Lee, Lieut. G. H.
Waring, 2nd Lieut. W. H.
Warren, 2nd Lieut. C.
Whyte, 2nd Lieut. A. J. L.
Yolland, 2nd Lieut. N. de C.

[The results relating to candidates who sat for the Examination abroad will be published later.]

## Accessions to the Reference Library.

AVERY, A. H. Dynamo design and construction. 8vo. 264 pp. *London*, [1922]

BIGELOW, F. H. Atmospheric radiation electricity and magnetism. [Supplement no. 4 to the Treatises on the atmospheres of the sun and the earth]. 8vo. 97 pp. *Vienna*, 1922

BRITISH ENGINE, BOILER & ELECTRICAL INSURANCE COMPANY, LTD. Technical report for 1922. sm. 4to. 184 pp. [*Manchester*, 1923]

COOPER, W. R. Electro-chemistry related to engineering. 8vo. 150 pp. *London*, 1923

COURSEY, P. R. How to build amateur valve stations. sm. 8vo. 70 pp. *London*, 1923

—— The radio experimenter's handbook. Part ii, Data and design. 8vo. 78 pp. *London*, 1923

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH. Report of the Fuel Research Board for the years 1922, 1923. First section : The production of air-dried peat. 8vo. 153 pp. *London*, 1923

DOVER, A. T. Traction motor control (Direct current). sm. 8vo. 124 pp. *London*, 1923

ESMARCH, W. Über die Elektrizitätsleitung in metallischen Aggregaten. [Aus : Jahrbuch der Radioaktivität und Elektronik, 19. Band, Heft 2]. 8vo. 21 pp. [*Leipzig*, 1922]

FLIGHT, W. S. Electrical insulation. The functions and characteristics of electrical insulating materials (solid, liquid, and gaseous) ; the testing of these materials ; and their use in the insulation of electrical machinery and apparatus. sm. 8vo. 118 pp. *London*, 1923

GILL, J. F., and TEAGO, F. J. Examples in electrical engineering. 2nd ed. sm. 8vo. 173 pp. *London*, 1923

GRIERSON, R. Electric lift equipment for modern buildings. A practical guide to its selection, installation, operation and maintenance. 8vo. 191 pp. *London*, 1923

GUILBERT, C. F. Essais des machines électriques. 8vo. 565 pp. *Paris*, 1922

HARRIS, P. W. Practical wireless sets for all. sm. 8vo. 77 pp. *London*, 1923

HAWKINS, C. C. The dynamo. Its theory, design and manufacture. 6th ed. vol. 2 (Continuous-current dynamos). 8vo. 338 pp. *London*, 1923

HENDERSON, J., and MARSHALL, C. W. A.C. protective systems and gear. A practical introduction to the methods and equipment used to protect high-tension alternating-current systems from the effects of faults, with notes on the latter, the determination of short-circuit current, and the testing of protective devices. sm. 8vo. 120 pp. *London,* 1923

HUYGHENS, C. Traité de la lumière.
sm. 8vo. 165 pp. *Paris,* 1920

HYDE, W. H. Telephone troubles and how to find them. 19th ed. sm. 8vo. 56 pp. *London* [1922]

INSTITUTION OF PETROLEUM TECHNOLOGISTS, THE. The petroleum industry. A brief survey of the technology of petroleum based upon a course of lectures given by members of the Institution of Petroleum Technologists, Petroleum Exhibition, Crystal Palace, 1920.
8vo. 346 pp. *London,* [1922]

JOHN FRITZ MEDAL, THE. [Biographical notices of the John Fritz medallists, 1905–22].
8vo. 127 pp. [*New York,* 1922]

KARAPETOFF, V. Experimental electrical engineering and manual for electrical testing. 3rd ed. vol. i.
8vo. 827 pp. *New York,* 1922

KENNELLY, A. E. Dissymmetrical electrical conducting networks. [Midwinter Convention, A.I.E.E., New York, Feb. 14–17, 1923].
4to. 11 pp. *n.p.,* [1923]

LÉMERAY, E. M. L'éther actuel et ses precurseurs (simple récit). Preface de L. Lecornu.
sm. 8vo. 150 pp. *Paris,* 1922

MACCALL, W. T. Alternating current electrical engineering. 8vo. 499 pp. *London,* 1923

MOUREU, C. Notions fondamentales de chimie organique. 6$^{e}$ éd. 8vo. 558 pp. *Paris,* 1919

PERRIN, J. Atoms. Authorized translation by D. Ll. Hammick. 2nd English ed.
8vo. 245 pp. *London,* 1923

PRACTICAL, THE, electrician's pocket book for 1923. 25th annual issue. Edited by H. T. Crewe.
sm. 8vo. 662 pp. *London,* [1923]

RÜDENBERG, R. Elektrische Schaltvorgänge und verwandte Störungserscheinungen in Starkstromanlagen. 8vo. 512 pp. *Berlin,* 1923

STEINMETZ, C. P. Four lectures on relativity and space. 8vo. 136 pp. *New York,* 1923

WORKMAN, E. W. Costing organization for engineers. With a foreword by A. P. M. Fleming.
8vo. 96 pp. *London,* 1923

# THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 40. October 1923. INSTITUTION NOTES. [Issued with No. 323 of the Journal.]

## Ordinary Meetings, 1923–1924.

The recent postcard vote among members having addresses in the London district has resulted in a majority being in favour of the hour of 6 p.m., which will accordingly be continued, except on 29th November, when the Meeting will be in two sessions, viz. 5.30 to 7 p.m. and 8 to 9.30 p.m.

The details of the voting are as follows :—

Voting cards were issued to 2 750 members of all classes, and replies were received from :

| | |
|---|---|
| Corporate Members | 400 |
| Graduates | 39 |
| Students | 138 |
| Associates | 19 |
| Total | 596 |

Totals of Preference Marks (divided by 10) allotted to the Various Alternative Meeting Times.

| | *6 p.m.* | *6.30 p.m.* | *7 p.m.* | *7.30 p.m.* | *8 p.m.* |
|---|---|---|---|---|---|
| Corporate Members | 2 368 | 1 596 | 1 374 | 1 106 | 1 155 |
| Graduates | 128 | 219 | 266 | 191 | 85 |
| Students | 404 | 656 | 829 | 646 | 345 |
| Associates | 132 | 65 | 47 | 43 | 32 |
| | 3 032 | 2 536 | 2 516 | 1 986 | 1 617 |

Totals of 100 per cent Preference Marks (divided by 10 and excluding Percentages less than 100).

| | *6 p.m.* | *6.30 p.m.* | *7 p.m.* | *7.30 p.m.* | *8 p.m.* |
|---|---|---|---|---|---|
| Corporate Members | 201 | 46 | 59 | 33 | 61 |
| Graduates | 8 | 8 | 12 | 9 | 2 |
| Students | 27 | 27 | 43 | 27 | 14 |
| Associates | 11 | 2 | 2 | 2 | 2 |
| | 247 | 83 | 116 | 71 | 79 |

## Ten-Year Index.

The Ten-Year Index to Volumes 48 to 59 (years 1912–1921) of the *Journal* is now ready. The price to the public is 10s. 6d. per copy, but members can obtain copies at 5s. 3d. each on application to the Secretary.

Copies are still available of the Ten-Year Indexes to Volumes 1–10 (years 1872–1882), 11 to 20 (years 1882–1891), 21 to 30 (years 1892–1901), and 31–47 (years 1901–1911), price 2s. 6d. each.

## Students' Premiums.

The following premiums, each of the value of £10, have been awarded by the Council for papers read before the Students' Sections during last session.

| *Author* | *Title of Paper* | *Where read* |
|---|---|---|
| F. A. Adcock, Ph.D., and E. H. Wells, Ph.D. | "Temperature Measurement with the Einthoven Galvanometer" | Birmingham |
| W. T. J. Atkins, B.Sc. (Eng.) | "Electric Line Calculations" | Bradford |
| H. E. Dance | "The Electric Battery Vehicle" | Liverpool |
| J. C. Read | "Steam Turbine Blading" | London |
| W. Stirling | "Wind-driven Generators" | Glasgow |

## Scholarships.

The following Scholarships have been awarded by the Council for 1923–24:—

*Salomons Scholarships (value* £50 *each)* :

F. J. Lane, (The University, Leeds).
James Linton (Heriot Watt College, Edinburgh).

*David Hughes Scholarships (value* £50 *each)* :

R. MacWhirter (Royal Technical College, Glasgow).
R. E. Banks (The University, Birmingham).

## Cooper's Hill War Memorial Medal and Premium.

Intending competitors are reminded that the latest date for receiving the MS. of papers submitted in connection with the above is the 31st December, 1923. Full particulars can be obtained from the Secretary of the Institution, Savoy Place, Victoria Embankment, London, W.C. 2.

## Electrical Research Association.

The issue of periodical Progress Reports has been discontinued by the British Electrical and Allied Industries Research Association. Members desiring information in regard to the work which is being carried on by the Association should apply to the Director of the Association, 19 Tothill-street, Westminster, S.W. 1.

## Accessions to the Lending Library.

AITKEN, W. Automatic telephone systems. vol. 2, Auxiliary services and private and branch exchanges. 4to. 240 pp. *London*, 1923

BOLTON, D. J. Electrical measuring instruments and supply meters. 8vo. 344 pp. *London*, 1923

BROUGHTON, H. H. The electric handling of materials. vol. 4, Machinery and methods. 4to. 354 pp. *London*, 1923

CONSTANTINESCO, G. Theory of wave transmission; a treatise on transmission of power by vibrations. 2nd ed. 8vo. 213 pp. *London*, 1922

COOPER, W. R. Electro chemistry related to engineering. 8vo. 150 pp. *London*, 1923

DALBY, W. E., *F.R.S.* Steam power. 2nd ed. 8vo. 779 pp. *London*, 1920

ELWELL, C. F. The Poulsen arc generator. 8vo. 192 pp. *London*, 1923

ERSKINE-MURRAY, J., *D.Sc.* Wireless telephones, and how they work. sm. 8vo. 84 pp. *London*, 1923

FLEMING, A. P. M., and PEARCE, J. G. Research in industry: the basis of economic progress. 8vo. 259 pp. *London*, 1922

FLIGHT, W. S. Electrical insulation. The functions and characteristics of electrical insulating materials (solid, liquid, and gaseous); the testing of these materials; and their use in the insulation of electrical machinery and apparatus. sm. 8vo. 118 pp. *London*, 1923

GRIERSON, R. Electric lift equipment for modern buildings; a practical guide to its selection, installation, operation and maintenance. 8vo. 190 pp. *London*, 1923

HERBERT, T. E. Telephony. An elementary exposition of the telephone system of the British Post Office. sm. 8vo. 883 pp. *London*, 1923

HOBART, H. M. Electric motors; their theory and construction. 3rd ed. vol. 2, chiefly concerning polyphase current. 8vo. 399 pp. *London*, 1923

KLINGENBERG, G. A 130 000 kilowatt power station: third volume of "Large electric power stations." 4to. 154 pp. *London*, 1922

MACCALL, W. T. Alternating current electrical engineering. 8vo. 499 pp. *London*, 1923

McKAY, R. F. The theory of machines. 2nd ed. 8vo. 448 pp. *London*, 1922

PENDER, H. Direct-current machinery; a text-book on the theory and performance of generators and motors. 8vo. 324 pp. *New York*, 1922

SCOTT-MAXWELL, J. M., *B.Sc.* Costing and price-fixing. 8vo. 223 pp. *London*, 1923

SMITH, A. B., and CAMPBELL, W. L. Automatic telephony. 2nd ed. 8vo. 441 pp. *New York*, 1921

STEINMETZ, C. P. Four lectures on relativity and space. 8vo. 136 pp. *New York*, 1923

—— Theory and calculation of alternating current phenomena. 5th ed. 3rd impr. 8vo. 501 pp. *New York*, 1916

WORKMAN, E. W. Costing organization for engineers. With foreword by A. P. M. Fleming. 8vo. 96 pp. *London*, 1923

## Accessions to the Reference Library.

ADLER, L. Die Feldschwächung bei Bahnmotoren. 8vo. 44 pp. *Berlin*, 1919

AITKEN, W. Automatic telephone systems. vol. 2, Auxiliary services and private and branch exchanges. 4to. 240 pp. *London*, 1923

BENISCHKE, G. Die asynchronen Wechselfeldmotoren. Kommutator- und Induktionsmotoren. 8vo. 114 pp. *Berlin*, 1920

—— Die Porzellan-Isolatoren. 94 pp. *Berlin*, 1921

—— Die wissenschaftlichen Grundlagen der Elektrotechnik. 6e Aufl. 8vo. 698 pp. *Berlin*, 1922

BERTHOLD, M. Die Verwaltungspraxis bei Elektrizitätswerken und elektrischen Strassen- und Kleinbahnen. Manuldruck. la. 8vo. 191 pp. *Berlin*, 1906

BOLLIGER, A. Die Hochspannungs-Gleichstrommaschine. Eine grundlegende Theorie. 8vo. 82 pp. *Berlin*, 1921

BOLTON, D. J. Electrical measuring instruments and supply meters. 8vo. 344 pp. *London*, 1923

BRITISH ALUMINIUM CO., LTD. Aluminium: facts and figures. (vest pocket edition). sm. 8vo. 56 pp. *London*, 1923

BUNET, P. Les transformateurs. 8vo. 632 pp. *Paris*, 1923

CAMPBELL, N. R. Modern electrical theory: Supplementary chapters. Chapter XV, Series spectra. 8vo. 115 pp. *Cambridge*, 1921

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH: RADIO RESEARCH BOARD. Special Report no. 1: A discussion of the practical systems of direction-finding by reception. By R. L. Smith-Rose & R. H. Barfield. 8vo. 27 pp. *London*, 1923

ELBOURNE, E. T. The costing problem. sm. 8vo. 145 pp. *London*, [1919]

ELWELL, C. F. The Poulsen arc generator. 8vo. 192 pp. *London*, 1923

EVERSHEIM, P. Angewandte Elektrizitätslehre. Ein Leitfaden für das elektrische und elektrotechnische Praktikum. 8vo. 221 pp. *Berlin*, 1916

FRAENCKEL, A. Theorie der Wechselströme. 2te Aufl. 8vo. 359 pp. *Berlin*, 1921

GAISBERG, S. VON. Herstellen und Instandhalten Elektrischer Licht- und Kraftanlagen. Ein Leitfaden für Nicht-Techniker. 9te Ausgabe. sm. 8vo. 143 pp. *Berlin*, 1920

GLAZEBROOK, *Sir* R., *K.C.B.*, *F.R.S.* A dictionary of applied physics. vol. 5, Aeronautics—Metallurgy—General Index. 8vo. 597 pp. *London*, 1923

GRABSCHEID, J. Elektromotoren. Ein Leitfaden zum Gebrauch für Studierende, Betriebsleiter und Elektromonteure. 8vo. 68 pp. *Berlin*, 1921

GROSSE, O. 40 Jahre Fernsprecher: Stephan-Siemens-Rathenau. 8vo. 94 pp. *Berlin*, 1917

GROTIAN, O. Die Geometrie der Gleichstrommaschine. 8vo. 134 pp. *Berlin*, 1917

GRÜNBERG, M. Verluste im Dielektrikum technischer Kondensatoren. 8vo. 42 pp. *Berlin*, 1916

Haas, A. The new physics. Lectures for laymen and others. Transl. by R. W. Lawson. sm. 8vo. 176 pp. *London*, 1923

Hallo, H. S. Leerbock der electrische tractie. Deel 1, Het rollend materieel. 8vo. 357 pp. *Delft*, 1923

Hoppe, F. Lexikon der Elektrizität und Elektrotechnik. 8vo. 966 pp. *Wien, n.d.*

Jasse, E. Die Berechnung der Anlass- und Regelwiderstände. 8vo. 177 pp. *Berlin*, 1921

Kemman. G. Die selbsttätige Signalanlage der Berliner Hoch- und Untergrundbahn, nebst einigen Vorläufern. Mit 15 Tafeln. la. 8vo. 193 pp. *Berlin*, 1921

Kosack, E. Elektrische Starkstromanlagen. Maschinen, Apparate, Schaltungen, Betrieb. 6e Auflage. 8vo. 342 pp. *Berlin*, 1923

Kummer, W. Die Maschinenlehre der elektrischen Zugförderung. Band 2, Die Energieverteilung für elektrische Bahnen. 8vo. 158 pp. *Berlin*, 1920

Kyser, H. Die elektrische Kraftübertragung. Band 2, Die Niederspannungs- und Hochspannungs-Leitungsanlagen. 2e Aufl. 8vo. 413 pp. *Berlin*, 1921

Larner, E. T. Alternating currents: their theory and transmission. sm. 8vo. 198 pp. *London*, 1923

Lvoff, M. The engineers' pocket technical dictionary. French-English. sm. 8vo. 150 pp. *London*, [1923]

Mills, J. Radio communication, theory and methods. With an appendix on transmission over wires. sm. 8vo. 216 pp. *London*, 1923

Morgan, J. D. Principles of electric spark ignition in internal combustion engines. Re-issue with an additional chapter. 8vo. 94 pp. *London*, 1922

Natalis, F. Die Berechnung von Gleich- und Wechselstromsystemen. Neue Gesetze über ihre Leistungs-aufnahme. 8vo. 37 pp. *Berlin*, 1920

Nesper, E. Handbuch der drahtlosen Telegraphie und Telephonie. 2 Bd[e]. 8vo. *Berlin*, 1921

Photography as a scientific implement. A collective work by [various authors]. 8vo. 557 pp. *London*, 1923

Richter, R. Ankerwicklungen für Gleich- und Wechselstrommaschinen. Berichtigter Manuldruck 1922. 8vo. 434 pp. *Berlin*, 1920

Ring, H. Die symbolische Methode zur Lösung von Wechselstromaufgaben. 8vo. 57 pp. *Berlin*, 1921

Skirl, W. Messgeräte und Schaltungen für Wechselstrom-Leistungsmessungen. 8vo. 278 pp. *Berlin*, 1920

Society of Motor Manufacturers and Traders. Register of charging stations for electric vehicles. la. 8vo. 32 pp. *London* [1923]

Strecker, K. Hilfsbuch für die Elektrotechnik. 9te Auflage. 8vo. 671 pp. *Berlin*, 1921

Thomälen, A. Kurzes Lehrbuch der Elektrotechnik. 9e Aufl. 8vo. 404 pp. *Berlin*, 1922

Trautvetter, K. Linienführung elektrischer Bahnen. 8vo. 190 pp. *Berlin*, 1920

Vidmar, M. Der wirtschaftliche Aufbau der elektrischen Maschine. 8vo. 118 pp. *Berlin*, 1918

War Office. Signals Experimental Establishment, Woolwich. Technical Report. Serial, nos. 22a, 23a. April, June, 1923. fol. [*Woolwich*, 1923]

Weyhausen, E. G., and Mettgenberg, P. Berechnung Elektrischer Förderanlagen. 8vo. 94 pp. *Berlin*, 1920

Willers, H. B. Die Nebenstellentechnik. 8vo. 178 pp. *Berlin*, 1920

Wirz, E. Beitrag zur Theorie und Untersuchung der Ferrarismessgeräte. 8vo. 133 pp. *Berlin*, 1912

## SUGGESTION FOR BINDING VOLUME 61.

When "Institution Notes" are bound with the *Journal* they should be inserted immediately after page 1160 and be followed by this Index.

# INDEX TO VOL. 61.

### 1923.

### EXPLANATION OF ABBREVIATIONS.

(P) indicates a reference to the general title or subject of a paper or address.
(p) indicates a reference to a subject dealt with in a paper or address of which the title is not quoted.
(D) indicates a reference to a discussion upon a paper or address of which the general title or subject is quoted
(d) indicates a reference to a subject dealt with in a discussion on a paper or address of which the general title is not quoted.

A.

*Abstracts* (*Science*), Council's report on. 598.
Accounts, Annual, for 1922. 604.
——, Annual, for 1922, Council's report on. 600.
——, Benevolent Fund, for 1922. 703.
Adcock, F., and Wells, E. H. Temperature measurement with Einthoven galvanometer. (P), 1115.
Addenbrooke, G. L. Speaking on Mr. E. E. Brooks's slides showing lines of electric force. (d), 1141.
Address of R. D. Archibald, as chairman of Dundee Sub-Centre. 21.
—— of F. G. C. Baldwin, as chairman of North-Eastern Centre. 24.
—— of A. S. Barnard, as chairman of North-Western Centre. 145.
—— of W. Cramp, as chairman of South Midland Centre. 136.
—— of F. Gill, as President. 1.
—— of F. Gill to London Students' Section. 788.
—— of A. S. Hampton, as chairman of Scottish Centre. 149.
—— of E. C. Handcock, as chairman of Irish Centre. 141.
—— of J. F. Nielson to Scottish Students' Section. 280.
—— of W. Pearson, as chairman of East Midland Sub-Centre. 37.
—— of W. P. Richmond, as chairman of Tees-side Sub-Centre. 157.
—— of F. Tremain, as chairman of Western Centre. 16.
—— of B. Welbourn, as chairman of Liverpool Sub-Centre. 31.
—— of H. West, as chairman of Sheffield Sub-Centre. 152.
—— of W. B. Woodhouse, as chairman of North Midland Centre. 35.
—— of C. H. Wordingham to London Students' Section. 277.
Adhesion between lithographic stone and metal plate. A. Johnsen and K. Rahbek, (p), 713.
Advertisements in *Journal*, Council's report on. 598.
Aerial, wireless. (*See* Telegraphy and Telephony).
Agriculture, Committee on Electricity in. 599.
——, electricity in. A. S. Barnard, (p), 146.
Aircraft, directional wireless telephony in. C. K. Chandler, (P), 803.
Air-space flux, calculation of. W. Cramp and (Miss) N. I. Calderwood, (P), 1061.
Alarm buzzer operated from central station. F. Tremain, (p), 20.
Alexander, T. R. Problems in high-speed alternators. (D), 888.
Allan, C. T. Variable-speed a.c. motors. (D), 962.
Allan, P. F.
  Current loading of paper cables. (D), 586.
  Domestic load building. (D), 207.
Allen, R. S. Works production. (D), 354.
Alternator. (*See* Generators, Electric).
Aluminium overhead wires, tests on. (P), 1013.
——, steel-cored, overhead wires, tests on. (P), 1041.
America (U.S.A.), electricity supply in. B. Welbourn, (p), 32.
——, Local Hon. Secretary for, G. Dunn appointed. 596.
——, telephone statistics of. F. G. C. Baldwin, (p), 25; F. Gill, (p), 11; B. Welbourn, (p), 31.
American Institute, wireless communication from. 612.
—— Institute's Convention at Niagara. 597.
Angwin, A. S. Radio tower design and wind pressure. (D), 413.
Appleton, E. V. Direct-reading thermionic voltmeter. (D), 306.
Appointments Board, Council's report on. 598.
Arc, iron welding. H. M. Sayers and F. M. Sayers, (P), 266.
—— welding apparatus. J. Caldwell, (P), 253; (D), 268.
Archibald, R. D.
  Address as chairman of Dundee Sub-Centre. 21.
  Apparatus for demonstrating magnetomotive forces in alternator windings. (p), 376.
Architect and electrical engineer, co-operation between. J. W. Beauchamp, (P), 728; (D), 736; F. Hooper, (P), 726; (D), 736.
Armature windings, distribution factor of. B. Hague and S. Neville, (D), 398.
Asbestos millboard, purchasing specification for. G. H. Nelson, (p), 352.
Ashton, K. B. Variable-speed a.c. motors. (D), 962.
Associazione Elettrotecnica Italiana, 25th anniversary of. 597.
Aston, C. J. Local conditions and radio direction-finding. (D), 194.
Atkins, W. T. J. Electric line calculations. (P), 1044.
Atkinson, Ll. B.
  Current loading of paper cables. (D), 579.
  Improvement of power factor. (D), 109.
  Speaking at Annual General Meeting, 1923. 1150.
  Speaking on liquidation of old Institution. 1150.
  Vote of thanks to J. S. Highfield for services as president. 65.
Atom, diagrammatic representation of. A. G. Warren, (p), 950.

Ayres, W. E. M. Improvement of power factor. (d), 112.

Ayrton, Hertha (Mrs.).
  Electric arc welding apparatus. (d), 268.
  Obituary notice. 1151.

## B.

Bache, W. J. Problems in high-speed alternators. (d), 870.

Bacon, F.
  Interconnection of a.c. power stations. (d), 499.
  Variable-speed a.c. motors. (d), 961.

Badham, L. H. L. Voltage maintenance by automatic substation. (d), 426.

Bailey, G. E. Works production. (d), 358.

Baily, F. G. Domestic load building. (d), 395.

Bainbridge-Bell, L. Direction-finding in steel ships. (d), 1058.

Baker, P. M.
  Domestic load building. (d), 205.
  Electric arc welding apparatus. (d), 272.
  Works production. (d), 355.

Balance, magnetic, new form of. W. P. Conly, (p), 161.

Baldwin, F. G. C.
  Address as chairman of North-Eastern Centre. 24.
  Voltage maintenance by automatic substation. (d), 427.

Barclay, S. F. Problems in high-speed alternators. (d), 880.

Barfield, R. H., and Smith-Rose, R. L. Effect of local conditions on direction-finding installations. (p), 179 ; (d), 195.

Barnard, A. S.
  Address as chairman of North-Western Centre. 145.
  Voltage maintenance by automatic substation. (d), 708.

Bartlett, A. T. Problems in high-speed alternators. (d), 887.

Barton, E. C. Co-operation of architect and electrical engineer. (d), 743.

Battery, storage, and power station auxiliaries. L. Breach and H. Midgley, (p), 836.

——, storage, in electricity supply. A. S. Barnard, (p), 146.

—— type of phase-advancer. T. F. Wall, (d), 119, 684.

—— vehicle, electric. H. E. Dance, (p), 1100.

Beaty, R. J. H. Underground transmission at 100 000 volts. (d), 249.

Beauchamp, J. W.
  Co-operation between architect and electrical engineer. (p), 728 ; (d), 746.
  Domestic load building. (d), 203.

Beaver, C. J. Underground transmission at 100 000 volts. (d), 239.

Benevolent Fund Accounts for 1922. 703.

—— Fund, Annual General Meeting of, 1923. 702.

—— Fund Committee, 1923–24. 702.

—— Fund Committee, report of, for 1922. 702.

—— Fund, Council's report on. 600.

—— Fund, donors to. 64, 702, 1139, 1148.

—— Fund, Wilde, transfer to new Institution. 404.

Benton, L. C. Voltage maintenance by automatic substation. (d), 704.

Berry, A. F. Domestic load building. (d), 203.

Berry, D. Underground transmission at 100 000 volts. (d), 383.

Bevan, C. G. Problems in high-speed alternators. (d), 870.

Binyon, B.
  Direct-reading thermionic voltmeter. (d), 306.
  Direction-finding in steel ships. (d), 1059.
  Local conditions and radio direction-finding. (d), 194.
  Revolving magnetic drum for relays, etc. (d), 928.

Bishop, D. H. Drive of power station auxiliaries. (d), 858.

Blades, H. W. Current loading of paper cables. (d), 593.

Booth, H. C., and Melsom, S. W. Rating of cables for intermittent loads. (p), 363.

Boyce, B. A. M. Problems in high-speed alternators. (d), 884.

Braid, G. G. Improvement of power factor. (d), 900.

Braking, regenerative, with d.c. traction, compound characteristic in. M. G. Say and H. G. Frampton, (p), 863.

Bramwell, H. P. Current loading of paper cables. (d), 589.

Brazil, H.
  Current loading of paper cables. (d), 580.
  Drive of power station auxiliaries. (d), 846.

Breach, L. Improvement of power factor. (d), 124.

Breach, L., and Midgley, H. Drive of power station auxiliaries. (p), 829 ; (d), 849, 856, 861.

Breakdowns of high-speed alternators. G. A. Juhlin, (d), 871 ; J. Rosen, (p), 439.

—— of power station auxiliaries. L. Breach and H. Midgley, (p), 831.

——, submarine cable, location of. F. B. Young and W. Jevons, (p), 822.

Brillouin, M. Letter from, to President. 65.

Britton, S. E. Domestic load building. (d), 211.

Broadcasting, wireless. (*See under* Telegraphy and Telephony).

Brooks, E. E. Slides showing lines of electric force. 1141.

Brown, A. C.
  Radio tower design and wind pressure. (d), 414.
  Revolving magnetic drum for relays, etc. (d), 928.

Brown, H. Works production. (d), 354.

Building Fund, donors to. 1139.

—— operations, electricity and. J. W. Beauchamp, (p), 734.

Buist, D. M.
  Power factor. (d), 689.
  Problems in high-speed alternators. (d), 475.

Burgess, W. A. A. Improvement of power factor. (d), 121.

Burnand, W. E.
  Improvement of power factor. (d), 121.
  Power factor. (d), 681.
  Works production. (d), 355.

Burr, J. W.
  Domestic load building. (d), 890.
  Improvement of power factor. (d), 896.
  Problems in high-speed alternators. (d), 869.
  Variable-speed a.c. motors. (d), 960.

Buttenshaw, H. F. Power factor. (d), 688.

Butterworth, S.
  Examination of Mie's formula. (p), 565.
  Inductances for high-frequency circuits. (d), 939.

Buzzer, alarm, operated from central station. F. Tremain, (p), 20.

Bye-laws, new, Council's report on. 594.

## C.

**CABLES AND CONDUCTORS.**
  [*Also see* Power Supply (Distribution and Transmission)].
  Cables for power station auxiliaries. L. Breach and H. Midgley, (p), 844.
  Capacities of triple-concentric cables. A. M. Taylor, (p), 235.
  Effect of shearing stress on span calculations. T. Ohtsuki, (p), 1079.
  E.H.T. cables in U.S.A. B. Welbourn, (p), 34.
  Electric line calculations. W. T. J. Atkins, (p), 1044.
  Feeders and fully automatic substation. P. J. Robinson, (p), 421.
  Grading of cables. A. M. Taylor, (p), 221.
  Lines of force from charged conductors. G. L. Addenbrooke, (d), 1141.

**CABLES AND CONDUCTORS** (*continued*).
Overhead aluminium cables, tests on. (p), 1013.
—— copper cables, tests on. (p), 997.
—— galvanized steel cables, tests on. (p), 1026.
—— steel-cored aluminium cables, tests on. (p), 1041.
Permissible current loading of paper-insulated cables. S. W. Melsom and E. Fawssett, (p), 517; (d), 579, 944.
Rating of cables for intermittent loads. S. W. Melsom and H. C. Booth, (p), 363.
Single-core sheathed cables for alternating currents. W. Cramp and (Miss) N. I. Calderwood, (p), 477.
Submarine cables, location of. F. B. Young and W. Jevons, (p), 822.
Telephone cables, early. F. Tremain, (p), 18.
—— cables, installing of, in buildings. J. Johnson, (d), 745.
—— cables, loading of. F. Gill, (p), 4.
Underground cables at 100 000 volts. A. M. Taylor, (p), 220; (d), 239, 382.
Calderwood, (Miss) N. I., and Cramp, W.
Calculation of air-space flux. (p), 1061.
Single-core cables for alternating currents. (p), 477.
Caldwell, J. Electric arc welding apparatus. (p), 253; (d), 275.
Carpenter, R. E. H. Revolving magnetic drum for relays, etc. (d), 927.
Carr, L. H. A.
Improvement of power factor. (d), 130.
Pulling into step of induction-type synchronous motor. (p), 692.
Works production. (d), 359.
Carter, A. F. Improvement of power factor. (d), 122.
Carter, T.
Domestic load building. (d), 208.
Improvement of power factor. (d), 117.
Works production. (d), 894.
Cascade motor. F. Creedy, (p), 323.
Cash, H. J. Co-operation of architect and electrical engineer. (d), 742.
Centres, Local, Council's report on. 596.
——, Local, technical libraries for. 596.
Chamberlain, Rt. Hon. Neville. Speaking at Annual Dinner, 1923. 402.
Chambers, F. J. Intensity of received radio signals. (d), 513.
Chamen, W. A. Problems in high-speed alternators. (d), 870.
Chandler, C. K. Directional wireless telegraphy in aircraft. (p), 803.
Chapman, F. T. Vibration in squirrel-cage motors. (p), 39.
Chattock, R. A.
Variable-speed a.c. motors. (d), 330.
Voltage maintenance by automatic substation. (d), 435.
Chaytor, A. R. Power factor. (d), 686.
Cheetham, G. A.
Improvement of power factor. (d), 133.
Voltage maintenance by automatic substation. (d), 426, 707.
Chemical properties of insulating oils, research on. (p), 661.
—— tests for unvarnished insulating papers. (p), 992.
Christie, J. C. Drive of power station auxiliaries. (d), 859.
Clarke, E. F. Obituary notice. 1151.
Clayton, A. E.
Distribution factor of armature windings. (d), 398.
M.M.F. of armature windings, theory of. (p), 749.
Clayton, A. V. Improvement of power factor. (d), 122.
Clinker, R. C. Direct-reading thermionic voltmeter. (d), 306.
Close, F. W. Variable-speed a.c. motors. (d), 331.
Clothier, H. W. Underground transmission at 100 000 volts. (d), 248.
Clothier, H. W. Voltage maintenance by automatic substation. (d), 430.
Clothier, T. D.
Drive of power station auxiliaries. (d), 853.
Underground transmission at 100 000 volts. (d), 386.
Coal distillation and power supply. W. B. Woodhouse, (p), 35.
——, efficiency of, for heating. J. W. Beauchamp, (p), 729.
Coal-cutters. J. C. Stewart, (p), 169.
Coil design for high-frequency circuits. C. L. Fortescue, (p), 933; (d), 939.
——, open-ended, stationary waves on. A. Press, (p), 405.
Colefax, Sir Arthur. Speaking at Annual Dinner, 1923. 402.
Collard, A. O. Co-operation of architect and electrical engineer. (d), 737.
Colleges. (*See* Education).
Collie, J. H.
Domestic load building. (d), 214.
Drive of power station auxiliaries. (d), 853.
Voltage maintenance by automatic substation. (d), 434.
Communication, long-distance. F. G. C. Baldwin, (p), 29; F. Gill, (p), 2.
Condenser carrying 7 amperes at 500 000 periods. M. D. Hart, (p), 700.
——, fringeing effect at edges of. G. L. Addenbrooke, (d), 1142.
Condensers and power factor improvement. G. Kapp, (p), 93.
——, calculation of capacity of. W. Cramp and (Miss) N. I. Calderwood, (p), 1069.
——, static and rotary, comparison between. H. E. Yerbury, (p), 680.
Conductors. (*See* Cables and Conductors).
Conly, W. P. Measurement of flux density. (p), 161.
Contractors, electrical, registration of. 599; A. S. Barnard, (p), 147; J. W. Beauchamp, (p), 735.
Contracts, Model General Conditions for. 599; W. Pearson, (p), 37.
Control gear. (*See* Switchgear).
—— of electric battery vehicle. H. E. Dance, (p), 1103.
—— of variable-speed a.c. motors. F. Creedy, (p), 310.
Conversazione, Annual, Council's report on. 597.
Converter, rotary, and power factor improvement. G. Kapp, (p), 99.
Cooking, electric. J. W. Beauchamp, (p), 732; F. Hooper, (p), 727.
—— load, electric, development of. W. A. Gillott, (p), 197.
Cooling of turbo-alternator rotor. H. W. Taylor, (d), 462.
Cooper, J. A.
Repeaters and long-distance telephony. (p), 75.
Voltage maintenance by automatic substation. (d), 437.
Cooper, W. J. Domestic load building. (d), 395.
Cooper, W. R.
Domestic load building. (d), 204.
Speaking at Annual General Meeting, 1923. 1150.
Co-operation. W. Pearson, (p), 37.
—— between architect and electrical engineer. J. W. Beauchamp, (p), 728; (d), 736; F. Hooper, (p), 726; (d), 736.
—— in electrical industry. W. A. Gillott, (d), 218; E. C. Handcock, (p), 145.
Copper overhead wires, tests on. (p), 997.
Corlett, G. S. Improvement of power factor. (d), 132.
Costing department of works. G. H. Nelson, (p), 348.
Costs, electricity supply. (*See* Power station).
——, manufacturing, and the engineer. F. C. Lawrence, (p), 52.
Cotton, H. Operation of induction motors in cascade. (p), 284.

Council, Engineering Joint. 599.
——, report of, for 1922–23. 594.
Cowie, J. R.
  Drive of power station auxiliaries. (d), 848.
  Works production. (d), 354.
Cramb, A. C. Domestic load building. (d), 204.
Cramp, W.
  Address as chairman of South Midland Centre. 136.
  Improvement of power factor. (d), 113.
  Underground transmission at 100 000 volts. (d), 243.
Cramp, W., and Calderwood, (Miss) N. I.
  Calculation of air-space flux. (p), 1061.
  Single-core cables for alternating currents. (p), 477.
Creedy, F. Variable-speed a.c. motors without commutators. (p), 309; (d), 333, 962.
Crompton, A. W. Domestic load building. (d), 209.
Crompton, W. E. V. Co-operation of architect and electrical engineer. (d), 743.
Cronin, B. Domestic load building. (d), 892.
Cross, W. Domestic load building. (d), 206.
Cubitt, H. Co-operation of architect and electrical engineer. (d), 742.
Current distribution in submarine cable. F. B. Young and W. Jevons, (p), 824.
——, alternating, from triodes, theory of. N. Shuttleworth, (p), 1121.

### D.

Dalton, W. T. Voltage maintenance by automatic substation. (d), 431.
Dance, H. E. Electric battery vehicle. (p), 1100.
Darby, J. C. H. Obituary notice. 1152.
Darling, C. R. Electric arc welding apparatus. (d), 269.
David, E. I.
  Improvement of power factor. (d), 897.
  Interconnection of a.c. power stations. (d), 496.
  Problems in high-speed alternators. (d), 869.
Davies, B. Revolving magnetic drum for relays, etc. (d), 929.
Davies, H. O. Domestic load building. (d), 891.
Dawson, C. Testing of materials. (p), 59.
Dearlove, A. L. Obituary notice. 1152.
Del Mar, W. A. Current loading of paper cables. (d), 584.
Depreciation, provision against. F. Gill, (p), 790.
Detector, electrode cable. F. B. Young and W. Jevons, (p), 825.
Devonshire, Sir James.
  Speaking at Annual General Meeting, 1923. 1149.
  Speaking on liquidation of old Institution. 1150.
Dewar, Sir James. Obituary notice. 1152.
Dickinson, H.
  Domestic load building. (d), 209.
  Drive of power station auxiliaries. (d), 855.
Dielectric. (*See* Insulation).
Dinner, Annual, Council's report on. 597.
——, Annual, proceedings at. 400.
Direction-finding, wireless. (*See* Telegraphy and Telephony).
Distribution of electricity. [*See* Power Supply (Distribution and Transmission)].
Domestic load building. W. A. Gillott, (p), 197; (d), 202, 392, 890.
Dorey, E. W. Improvement of power factor. (d), 113.
Downie, F. H.
  Problems in high-speed alternators. (d), 875.
  Variable-speed a.c. motors. (d), 332.
Dunn, G. Appointed Local Hon. Secretary for U.S.A. 596.
Dunsheath, P.
  Current loading of paper cables. (d), 582.
  Underground transmission at 100 000 volts. (d), 242.
Dutch Royal Institute of Engineers, 75th anniversary of. 597.
Dykes, A. H. Co-operation of architect and electrical engineer. (d), 736.

### E.

Eccles, W. H.
  Radio tower design and wind pressure. (d), 412.
  Transoceanic wireless telephony. (d), 820.
Eck, J. Co-operation of architect and electrical engineer. (d), 739.
Eckersley, T. L.
  Inductances for high-frequency circuits. (d), 940.
  Intensity of received radio signals. (d), 512.
Economics and engineering. F. Gill, (p), 788.
—— of railway electrification. A. S. Hampton, (p), 149.
Edgcumbe, K.
  Improvement of power factor. (d), 110.
  Works production. (d), 353.
Education, electrical, in early days. F. Tremain, (p), 16.
—— Research Fund grant to R. H. Holmes. 597.
——, technical. F. Gill, (p), 1.
——, technical, in Ireland. E. C. Handcock, (p), 144.
Elections. 293, 610, 700, 801, 1143, 1147.
Electrical engineer. (*See* Engineers, electrical).
Electricity supply. (*See* Power Supply).
Electro-adhesion effect. A. Johnsen and K. Rahbek, (p), 713.
Electrode apparatus for location of submarine cables and faults. F. B. Young and W. Jevons, (p), 822.
Electrolytic conductors, adhesion of. A. Johnsen and K. Rahbek, (p), 713.
Electromagnetic. (*Also see* Magnetic).
—— waves, length of. A. G. Warren, (p), 949.
Electronic bombardment, spectrum emitted under. A. G. Warren, (p), 949.
Electroscope, pocket. A. Johnsen and K. Rahbek, (p), 719.
Electrostatic attraction or adhesion. A. Johnsen and K. Rahbek, (p), 713.
—— lines of force, slides showing. G. L. Addenbrooke, (d), 1141.
Ellefsen, O. Voltage maintenance by automatic substation. (d), 710.
Elliptic functions, note on. W. Cramp and (Miss) N. I. Calderwood, (p), 1070.
Ellis, H. S. Problems in high-speed alternators. (d), 870.
Elwell, C. F. Design of radio towers: wind pressure assumptions. (p), 407; (d), 415.
Engineering, economics in. F. Gill, (p), 788.
—— Joint Council, Council's report on. 599.
Engineers and manufacturing costs. F. C. Lawrence, (p), 52.
——, electrical, co-operation between architects and. J. W. Beauchamp, (p), 728; (d), 736; F. Hooper, (p), 726; (d), 736.
——, young, advice to. J. F. Nielson, (p), 282; C. H. Wordingham, (p), 277.
Erskine-Murray, J. Intensity of received radio signals. (d), 510.
Ewen, H. Revolving magnetic drum for relays, etc. (d), 927.
Examinations, Associate Membership. 595.

### F.

Factory. (*See* Manufacturing *and also* Works).
Faraday Medal awarded to O. Heaviside, 1922. 595.
—— Medal awarded to Sir C. A. Parsons, 1923. 595, 701, 1144.

Faults, cable. (*See* Breakdowns).
Fawssett, E., and Melsom, S. W. Current loading of paper-insulated cables. (p), 517; (d), 944.
Fedden, S. E.
  Improvement of power factor. (d), 114.
  Problems in high-speed alternators. (d), 475.
Ferranti, S. Z. de. Speaking on award of Faraday Medal to Sir C. A. Parsons. 1145.
Fibre, vulcanized, directions for research on. (p), 964.
Fidoe, J. W. Interconnection of a.c. power stations. (d), 498.
Fleming, J. A.
  Elected honorary member. 294, 595.
  Problems in telephony. (p), 613.
  Speaking on election as honorary member. 403.
  Underground transmission at 100 000 volts. (d), 239.
  Vote of thanks to, for Kelvin Lecture. 1146.
Fletcher, G. H. Power factor. (d), 685.
Flood, W. H. Electric arc welding apparatus. (d), 272.
Fluids, Newton's theory for. C. F. Elwell, (p), 407.
Flux, magnetic. (*See* Magnetic).
Force, electric lines of, lantern slides showing. G. L. Addenbrooke, (d), 1141.
Forrest, F.
  Underground transmission at 100 000 volts. (d), 250.
  Voltage maintenance by automatic substation. (d), 436.
Fortescue, C. L.
  Direct-reading thermionic voltmeter. (d), 304.
  Inductances for high-frequency circuits. (p), 933; (d), 942.
  Radio tower design and wind pressure. (d), 414.
Frampton, H. G., and Say, M. G. Compound characteristic in regenerative braking with d.c. traction. (p), 863.
Fraser, H. G. Domestic load building. (d), 214.
Fraser, J. Obituary notice. 1152.
French, W. E.
  Current loading of paper cables. (d), 587.
  Voltage maintenance by automatic substation. (d), 428.
Frequencies, wireless, dielectric losses at. M. D. Hart, (p), 697.
Frith, J. Voltage maintenance by automatic substation. (d), 708.
Frome, N. F., and Robertson, D. Electrical timing device. (p), 49.
Fry, E. R. Improvement of power factor. (d), 133.
Fuel. (*See* Coal).
Fuller, W. P. Transmission by underground cables at 100 000 volts. (d), 386.
Furnaces, electric. H. West, (p), 154.
Furness, P. Domestic load building. (d), 214.

## G.

Galvanized steel overhead wires, tests on. (p), 1026.
Galvanometer, Einthoven, temperature measurement with. F. Adcock and E. H. Wells, (p), 1115.
Gamlen, R. E. Domestic load building. (d), 215.
Ganapati, S. V., and Parikh, R. G. Induction motors as synchronous machines. (p), 795.
Garrard, C. C. Voltage maintenance by automatic substation. (d), 437.
Gas and electric cookers, comparison of. O. C. Waygood, (d), 211.
—— apparatus, efficiency of. J. W. Beauchamp, (p), 729.
—— lighting in trains. A. S. Barnard, (p), 145.
Gavey, Sir John.
  Obituary notice. 1153.
  Vote of condolence with family of. 404.
Generation, a.c., by triodes. N. Shuttleworth, (p), 1121.
——, h.t., for deep therapy. C. H. Holbeach, (p), 369.

**GENERATORS, ELECTRIC.**
  (*Also see* Motors, Electric).
  Air-space flux. W. Cramp and (Miss) N. I. Calderwood, (p), 1061.
  Cooling of turbo-alternators. R. D. Archibald, (p), 23.
  Demonstrating M.M.F.'s of alternator windings. R. D. Archibald, (p), 376.
  Developments since 1902. R. D. Archibald, (p), 21.
  Distribution factor of armature windings. B. Hague and S. Neville, (d), 398.
  Drive of power station auxiliaries. L. Breach and H. Midgley, (p), 829; (d), 845.
  Economics of generator design. F. Gill, (p), 792.
  Leakage flux between pole-cores. B. Hague, (p), 1072.
  Limits of output. R. D. Archibald, (p), 22.
  M.M.F. of armature windings. A. E. Clayton, (p), 749.
  Problems in high-speed alternators. J. Rosen, (p), 439; (d), 458, 869.
  Water-cooling of turbo rotor. H. W. Taylor, (d), 462.
  Wind-driven generators. W. Stirling, (p), 1096.
Gibbins, J. Works production. (d), 894.
Gill, F.
  Address as President. 1.
  Address to London Students' Section. 788.
  Portrait of. *Frontispiece.*
  Presentation of Faraday Medal to Sir C. A. Parsons. 1145.
  Presentation of Thompson Library, etc. 1147.
  Speaking at Annual Dinner, 1923. 401.
  Speaking at Annual General Meeting, 1923. 1146, 1147, 1149.
  Vote of thanks to, for presidential address. 66.
  Vote of thanks to J. S. Highfield for services as president. 65.
  War Memorial Fund scholarships. 1144.
  Wilde Benevolent Fund. 404.
  Wireless telephonic communication with New York. 612.
Gillott, W. A.
  Co-operation of architect and electrical engineer. (d), 744.
  Domestic load building. (p), 197; (d), 216, 397, 892.
Glazebrook, Sir R. T. Vote of thanks to F. Gill for presidential address. 66.
Gray, A. Radio tower design and wind pressure. (d), 414.
Groves, W. E.
  Current loading of paper cables. (d), 593.
  Voltage maintenance by automatic substation. (d), 436.

## H.

Hague, B. Leakage flux between pole-cores. (p), 1072.
Hague, B., and Neville, S. Distribution factor of armature windings. (d), 399.
Haigh, T. H. Variable-speed a.c. motors. (d), 961.
Hall, S. E.
  Domestic load building. (d), 215.
  Power factor. (d), 689.
Hall, T. Problems in high-speed alternators. (d), 884.
Hamilton, J. Drive of power station auxiliaries. (d), 852.
Hampton, A. S.
  Address as chairman of Scottish Centre. 149.
  Domestic load building. (d), 395.
  Improvement of power factor. (d), 902.
Handcock, E. C. Address as chairman of Irish Centre. 141.
Hansford, R. V. Inductances for high-frequency circuits. (d), 942.
Hardie, R. Domestic load building. (d), 393.
Harmer, A. F. Co-operation of architect and electrical engineer. (d), 740.
Harrison, H. H. Revolving magnetic drum for relays, etc. (d), 929.

Hart, M. D. Dielectric losses at wireless frequencies. (p), 697.
Harvey, G. M. Variable-speed a.c. motors. (d), 331.
Haslam, S. B. Domestic load building. (d), 891.
Haulage, electric, in mines. J. C. Stewart, (p), 169.
Head, H. C. Obituary notice. 1154.
Heat, specific, of transformer oils. (p), 671.
Heating, electric. J. W. Beauchamp, (p) 732; F. Hooper, (p), 727.
——, electric, of water. F. Tremain, (p), 19.
—— of cables with intermittent loads. S. W. Melsom and H. C. Booth, (p), 363.
—— load, electric, development of. W. A. Gillott, (p), 197.
—— of alternator end-windings. J. Rosen, (d), 476.
—— of buried cables, second report on. S. W. Melsom and E. Fawssett, (p), 517; (d), 579, 944.
Heaviside, A. W. Obituary notice. 1154.
Heaviside, O. Faraday medal awarded to. 595.
Hellier, W. H. M. David Hughes Scholarship awarded to. 597.
Henderson, G. Voltage maintenance by automatic sub-station. (d), 711.
Henzell, G. P. Problems in high-speed alternators. (d), 475.
Herbert, T. E. Works production. (d), 361.
Heslop, J. M. Improvement of power factor. (d), 116.
Higgs, W. F. Works production. (d), 353.
Higham, H. Improvement of power factor. (d), 125.
Highfield, J. S.
  Award of Faraday Medal to Sir C. A. Parsons. 1144.
  Drive of power station auxiliaries. (d), 846.
  Speaking at Annual Dinner, 1923. 402.
  Speaking on liquidation of old Institution. 1150.
  Underground transmission at 100 000 volts. (d), 241.
  Vote of thanks to, for services as president. 65.
Highfield, W. E. Drive of power station auxiliaries. (d), 848.
Hill, E. P.
  Improvement of power factor. (d), 133.
  Voltage maintenance by automatic substation. (d), 708.
Hill, E. W. Improvement of power factor. (d), 115.
Hill, N. B. Problems in high-speed alternators. (d), 463.
Hird, W. B. Drive of power station auxiliaries. (d), 860.
Hobart, H. M. Electric arc welding apparatus. (d), 269.
Holbeach, C. H. Generation, h.t., for deep therapy. (p), 369.
Holland; anniversary of Royal Institute of Engineers. 597.
Hollingsworth, E. M. Improvement of power factor. (d), 124.
Hollingworth, J.
  Direct-reading thermionic voltmeter. (d), 304.
  Electric intensity of received signals. (p), 501; (d), 514.
  Field strength of Horsea wireless station. (d), 308.
  Local conditions and radio direction-finding. (d), 192.
Holmes, J. H. Problems in high-speed alternators. (d), 875.
Holmes, R. H. Awarded educational grant. 597.
Holttum, W. Underground transmission at 100 000 volts. (d), 385.
Honorary members. 294, 403, 595.
Honours conferred on members. 595.
Hooper, F. Co-operation between architect and electrical engineer. (p), 726; (d), 745.
Horton, C. E.
  Local conditions and radio direction-finding. (d), 193.
  Wireless direction-finding in steel ships. (p), 1049; (d), 1060.
Houghton, T. E.
  Drive of power station auxiliaries. (d), 853.
  Improvement of power factor. (d), 126.
Howe, G. W. O.
  Inductances for high-frequency circuits. (d), 942.
  Problems in high-speed alternators. (d), 470.
  Radio tower design and wind pressure. (d), 414.
  Underground transmission at 100 000 volts. (d), 382.
Howell, J. C. Variable-speed a.c. motors. (d), 961.
Hughes, C. T. Local conditions and radio direction-finding. (d), 194.
Hughes (David) Scholarship. Awarded to W. H. M. Hellier. 597.
Hunt, L. J. Variable-speed a.c. motors. (d), 326.
Hunter, P. V.
  Current loading of paper cables. (d), 583.
  Underground transmission at 100 000 volts. (d), 240.
Hurford, G. Works production. (d), 353.
Hutchinson, J. Y. Current loading of paper cables. (d), 587.
Hydro-electric. (*See* Power Supply).
Hysteresis. (*Also see* Magnetic).
—— loss with 100 000-volt cables. A. M. Taylor, (p), 229.

I.

Inductances for high-frequency circuits. C. L. Fortescue, (p), 933; (d), 939.
Industry, electrical, in Ireland. E. C. Handcock, (p), 141.
Ingleby, J. C. B. Variable-speed a.c. motors. (d), 330.

**INSTITUTION OF ELECTRICAL ENGINEERS.**
  Liquidation of old Institution. 594.
  —— of old Institution: Special General Meeting. 1150.
  Organization of the Institution. 603.
  Representation on other bodies. 603.
  The Institution. W. Cramp, (p), 137; F. Gill, (p), 1; E. C. Handcock, (p), 141.
Instituut (Koninglijk) van Ingenieurs, 75th anniversary of. 597.

**INSTRUMENTS.**
  Electrical timing device. D. Robertson and N. F. Frome, (p), 49.
  Meters and kVA tariffs. H. E. Yerbury, (p), 678.
  Meters for low power factors. G. Kapp, (p), 105.
  Recorders, relays, etc., application of revolving magnetic drum to. N. W. McLachlan, (p), 903; (d), 926.
  Temperature measurement with Einthoven galvanometer. F. Adcock and E. H. Wells, (p), 1115.
  Voltmeter, direct-reading thermionic. E. B. Moullin, (p), 295; (d), 304.

**INSULATION.**
  Dielectric loss at wireless frequencies, bridge method for. M. D. Hart, (p), 697.
  Dielectric loss in 100 000-volt cables. A. M. Taylor, (p), 236.
  Insulating oils, research on properties of. (p), 661.
  Insulating papers, unvarnished, research on. (p), 982.
  Liquid dielectric, alternating electric stress and. G. L. Addenbrooke, (d), 1142.
  Pressboard for insulating purposes, research on. (p), 486.
  Stator windings, insulation of. J. Rosen, (p), 444.
  Testing of insulating materials. C. Dawson, (p), 61.
  Vulcanized fibre, research on. (p), 964.
International Electrotechnical Commission, Council's report on. 600.
Ireland, electrical manufacturing in. E. C. Handcock, (p), 143.
——, water power schemes in. E. C. Handcock, (p), 141.
Irish Free State, Advisory Committee for. 599.

Iron. (*Also see* Steel).
—— industry, electric power in. W. P. Richmond, (p), 158 ; H. West, (p), 152.
—— welding arc. H. M. Sayers and F. M. Sayers, (p), 266.
Isaacs, R. G.
  Domestic load building. (d), 892.
  Improvement of power factor. (d), 898.
  Problems in high-speed alternators. (d), 869.
  Variable-speed a.c. motors. (d), 960.
Italian Electrotechnical Association, 25th anniversary of. 597.

J.

Jack, H. Variable-speed a.c. motors. (d), 328.
Jackson, Sir Henry.
  Direction-finding in steel ships. (d), 1059.
  Intensity of received radio signals. (d), 510.
  Local conditions and radio direction-finding. (d), 193.
Jackson, J. W.
  Problems in high-speed alternators. (d), 874.
  Variable-speed a.c. motors. (d), 333.
James, S. Power factor. (d), 683.
Jenkins, D.
  Domestic load building. (d), 891.
  Interconnection of a.c. power stations. (d), 498.
  Variable-speed a.c. motors. (d), 961.
Jepson, A. E. Power factor. (d), 683.
Jevons, W., and Young, F. B. Apparatus for location of submarine cables and faults. (p), 822.
Jockel, L. M. Drive of power station auxiliaries. (d), 847.
Johnsen, A., and Rahbek, K. A physical phenomenon and its application to telephony, etc. (p), 713.
Johnson, J. Co-operation of architect and electrical engineer. (d), 745.
Jones, I. Interconnection of a.c. power stations. (d), 497.
Jones, S. D. Problems in high-speed alternators. (d), 475.
Joseph, H. Problems in high-speed alternators. (d), 888.
Joseph, J. Revolving magnetic drum for relays, etc. (d), 927.
*Journal*, Council's report on. 598.
Joynson-Hicks, Sir W. Speaking at Annual Dinner, 1923. 401.
Juhlin, G. A.
  Problems in high-speed alternators. (d), 871, 876.
  Voltage maintenance by automatic substation. (d), 705.

K.

Kahn, M. L.
  Problems in high-speed alternators. (d), 888.
  Variable-speed a.c. motors. (d), 330.
Kapp, G.
  Improvement of power factor. (p), 89.
  Life and work of. Ll. B. Atkinson, (d), 109 ; W. Cramp, (p), 136.
Kapp, R. O. Improvement of power factor. (d), 899.
Keats, G. W. Co-operation of architect and electrical engineer. (d), 745.
Kelly, A. E. Improvement of power factor. (d), 901.
Kelvin Lecture, fourteenth : Problems in telephony. J. A. Fleming, (p), 613.
Kennedy, Lord Angus. Electric arc welding apparatus. (d), 273.
Kennedy, R. S. Electric arc welding apparatus. (d), 273.
Kennedy-Purvis, C. E. Direction-finding in steel ships. (d), 1056.
Kristiansen, M. L. Appointed Local Hon. Secretary for Norway. 596.
Kuyser, J. A. Problems in high-speed alternators. (d), 881.

L.

Labour and works committees. A. S. Barnard, (p), 148.
—— and works production. G. H. Nelson, (p), 338.
Lakeman, B. Current loading of paper cables. (d), 592.
Lamb, H. C.
  Improvement of power factor. (d), 131.
  Problems in high-speed alternators. (d), 877.
  Voltage maintenance by automatic substation. (d), 706.
Lambourn, W. C. Domestic load building. (d), 207.

**LAMPS AND LIGHTING.**
  Applications of electric lighting. F. Hooper, (p), 726.
  Church lighting. J. W. Beauchamp, (p), 731.
  Comparison of electricity and gas. J. W. Beauchamp, (p), 729.
  Electric light and eyesight. J. W. Beauchamp, (p), 731.
  —— lighting in mines. J. C. Stewart, (p), 173.
  —— lighting progress on ships. J. F. Nielson, (p), 280.
  Lighting tariff for domestic supply. W. A. Gillott, (p), 198.
Lawrence, F. C. The engineer and manufacturing costs. (p), 52.
Lawson, W. Underground transmission at 100 000 volts. (d), 251.
Lea, N. Direction-finding in steel ships. (d), 1056.
Leakage flux between pole-cores. B. Hague, (p), 1072.
Leatheroid, directions for research on. (p), 964.
Leeson, B. H. Voltage maintenance by automatic substation. (d), 432.
Lefroy, H. P. T.
  Direct-reading thermionic voltmeter. (d), 304.
  Direction-finding in steel ships. (d), 1059.
  Intensity of received radio signals. (d), 511.
  Local conditions and radio direction-finding. (d), 193.
  Revolving magnetic drum for relays, etc. (d), 928.
Libraries, technical, for Local Centres. 596.
Library, Council's report on. 597.
——, donors to. 294.
——, Thompson, presentation of. 1146.
Lifts, electric. J. W. Beauchamp, (p), 734.
Lighting. (*See* Lamps and Lighting).
Line, W. J.
  Underground transmission at 100 000 volts. (d), 251.
  Variable-speed a.c. motors. (d), 331.
Lines of electric force, slides showing. G. L. Addenbrooke, (d), 1141.
——, overhead power. (*See* Power Supply).
——, telegraph and telephone. (*See* Telegraphy and Telephony).
Lipman, C. L. Improvement of power factor. (d), 111.
Liquidation of old Institution. 594, 1150.
Load factor : effect on costs. A. S. Barnard, (p), 147.
Loan repayment periods. F. Gill, (p), 792 ; G. W. Keats, (d), 745.
Locomotives. (*See* Traction).
Longman, R. M.
  Current loading of paper cables. (d), 588.
  Improvement of power factor. (d), 899.
  Power factor. (d), 688.
  Voltage maintenance by automatic substation. (d), 430.
Lunnon, F. C.
  Direct-reading thermionic voltmeter. (d), 304.
  Inductances for high-frequency circuits. (d), 940.

M.

McClelland, W. Electric arc welding apparatus. (d), 271.
McColl, A. E. Improvement of power factor. (d), 901.

McColl, A. E.
  Problems in high-speed alternators. (d), 469.
  Underground transmission at 100 000 volts. (d), 382.
MacGregor-Morris, J. T., and Mallett, E. Resonant vibrations of telephone receiver diaphragms. (p), 1134.
Machine production chart. G. H. Nelson, (p), 346.
Machinery, electrical. (*Also see* Generators, Electric).
——, electrical, development of. R. D. Archibald, (p), 21.
McLachlan, N. W. Application of revolving magnetic drum to electric relays, etc. (p), 903 ; (d), 930.
MacLean, A. B. Improvement of power factor. (d), 118.
MacWhirter, A. C. Domestic load building. (d), 891.
Maggs, A. H. Salomons Scholarship awarded to. 597.
Magnetic drum, revolving, applied to electric relays, etc. N. W. McLachlan, (p), 903 ; (d), 926.
—— field of pole-changing motor. F. J. Teago, (p), 1087.
—— flux density, measurement of. W. P. Conly, (p), 161.
—— flux in air space, calculation of. W. Cramp and (Miss) N. I. Calderwood, (p), 1061.
—— leakage flux between pole-cores. B. Hague, (p), 1072.
Magnetomotive force of armature windings, theory of. A. E. Clayton, (p), 749.
—— of alternator windings, apparatus for demonstrating. R. D. Archibald, (p), 376.
Magnets, permanent, properties, etc., of. E. A. Watson, (p), 641.
Mains. (*See* Cables and Conductors).
Mallalieu, V. Improvement of power factor. (d), 133.
Mallett, E., and MacGregor-Morris, J. T. Resonant vibrations of telephone receiver diaphragms. (p), 1134.
Mallinson, A. B.
  Current loading of paper cables. (d), 591.
  Improvement of power factor. (d), 132.
  Problems in high-speed alternators. (d), 882.
  Voltage maintenance by automatic substation. (d), 707.
  Underground transmission at 100 000 volts. (d), 386.
  Works production. (d), 360.
Malpas, A. E.
  Drive of power station auxiliaries. (d), 852.
  Improvement of power factor. (d), 128.
  Underground transmission at 100 000 volts. (d), 385.
Manufactured goods, British, Council's report on. 599.
Manufacturing. (*Also see* Works).
—— costs and the engineer. F. C. Lawrence, (p), 52.
——, electrical, in Ireland. E. C. Handcock, (p), 143.
Marchant, E. W.
  Current loading of paper cables. (d), 581.
  Improvement of power factor. (d), 127.
  Intensity of received radio signals. (d), 513.
  Underground transmission at 100 000 volts. (d), 387.
  Voltage maintenance by automatic substation. (d), 425.
Marshall, C. W.
  Improvement of power factor. (d), 899.
  Problems in high-speed alternators. (d), 468.
  Underground transmission at 100 000 volts. (d), 383.
Martin, D. Voltage maintenance by automatic substation. (d), 711.
Masters, F. H. Co-operation of architect and electrical engineer. (d), 736.
Masts, radio, and wind pressure. C. F. Elwell, (p), 407 ; (d), 412.
Materials, insulating. (*See* Insulation).
——, testing of. C. Dawson, (p), 59.
——, X-ray examination of. A. G. Warren, (p), 949.
Mather, J. F. Problems in high-speed alternators. (d), 474.
Meares, J. W. Presentation to. 612.
Mears, A. Domestic load building. (d), 393.
Measurement of flux density in air path. W. P. Conly, (p), 161.
Measurement, temperature, with Einthoven galvanometer. F. Adcock and E. H. Wells, (p), 1115.
Medal, Faraday, awarded to O. Heaviside, 1922. 595.
——, Faraday, awarded to Sir C. A. Parsons, 1923. 595, 701, 1144.
Medlyn, W. J.
  Current loading of paper cables. (d), 591.
  Works production. (d), 358.
Meeting, Annual General, 1923, proceedings at. 1146.
——, Special General, on liquidation of old Institution. 1150.
——, Summer, Council's report on. 597.
Meetings, attendances at. 596.
—— held, list of. 601.
——, Informal, Council's report on. 596.
Melsom, S. W., and Booth, H. C. Rating of cables for intermittent loads. (p), 363.
Melsom, S. W., and Fawssett, E. Current loading of paper-insulated cables. (p), 517 ; (d), 944.
Melton, G. B. Problems in high-speed alternators. (d), 474.
Member, honorary, J. A. Fleming elected. 294, 403, 595.
Members, deceased, list of. 595.
——, honorary. 294, 403, 595.
——, honours conferred on. 595.
Membership of Institution. 594, 601.
Memorial (War) Fund, scholarships in connection with. 1144.
——, war, unveiling of. 595.
Memorials, war, functions of. A. S. Barnard, (p), 148.
Mensforth, H. Works production. (d), 352.
Mercer, F. Underground transmission at 100 000 volts. (d), 388.
Metals, testing of. C. Dawson, (p), 59.
——, X-ray examination of. A. G. Warren, (p), 949.
Meters. (*See* Instruments).
Mica and rotor end-rings ; moulding specification. G. H. Nelson, (p), 351.
Midgley, H. Improvement of power factor. (d), 899.
Midgley, H., and Breach, L. Drive of power station auxiliaries. (p), 829 ; (d), 849, 856, 861.
Miller, Herbert William. Works production. (d), 893.
Miller, Herbert Woodville. Obituary notice. 1155.
Mills, rolling, electric power in. W. P. Richmond, (p), 158 ; H. West, (p), 153.
Mines, electricity as applied to. J. C. Stewart, (p), 167.
——, ventilation of. F. Hooper, (p), 727.
Mitchell, H. E. Obituary notice. 1155.
Mitchell, R. B.
  Domestic load building. (d), 392.
  Drive of power station auxiliaries. (d), 858.
  Voltage maintenance by automatic substation. (d), 709.
Moisture detection and alternator ventilation. J. Rosen, (d), 472.
Model General Conditions. (*See* Contracts).
Mordey, W. M. Presentation of Thompson Library. 1146.
Morris, G. H. Voltage maintenance by automatic substation. (d), 425.
Morrish, H. E. Transoceanic wireless telephony. (d), 821.
Morton, J. Problems in high-speed alternators. (d), 887.

**MOTORS, ELECTRIC.**

  (*Also see* Generators, Electric).
  Compound characteristic in regenerative braking. M. G. Say and H. G. Frampton, (p), 863.
  Electric battery vehicle, motor of. H. E. Dance, (p), 1101.
  For power station auxiliaries. L. Breach and H. Midgley, (p), 845.

**MOTORS, ELECTRIC** (*continued*).
  For use in mines. J. C. Stewart, (p), 167.
  In iron and steel industry. W. P. Richmond, (p), 158 ; H. West, (p), 154.
  Induction motors as synchronous machines. S. V. Ganapati and R. G. Parikh, (p), 795.
  —— motors in cascade. H. Cotton, (p), 284.
  Leakage flux between pole-cores. B. Hague, (p), 1072.
  Squirrel-cage motors, noise and vibration in. F. T. Chapman, (p), 39.
  Stator field of 3-phase motor. F. J. Teago, (p), 1087.
  Synchronous induction motor and power factor improvement. G. Kapp, (p), 94.
  —— induction motor, pulling into step of. L. H. A. Carr, (p), 692.
  Variable-speed a.c. motors without commutators. F. Creedy, (p), 309 ; (d), 326, 960.

Moullin, E. B.
  Direct-reading thermionic voltmeter. (p), 295 ; (d), 306.
  Field strength of Horsea wireless station. (p), 67 ; (d), 308.
  Intensity of received radio signals. (d), 511.
Moxon, E. Domestic load building. (d), 212.
Munby, A. E. Co-operation of architect and electrical engineer. (d), 738.
Muncaster, F. W. Domestic load building. (d), 208.
Munro, D. S. Domestic load building. (d), 396.
Murray, D. Revolving magnetic drum for relays, etc. (d), 928.
Museum, Council's report on. 597.
——, donors to. 403, 598.

N.

Nairn, W. Interconnection of a.c. power stations. (d), 497.
Nancarrow, F. E. Inductances for high-frequency circuits. (d), 941.
Nelson, G. H. Works production. (p), 338 ; (d), 356, 361, 895.
Nelson, J. E. Domestic load building. (d), 210.
Nelson, R. Improvement of power factor. (d), 899.
Neville, S., and Hague, B. Distribution factor of armature windings. (d), 399.
Nichols, H. W. Transoceanic wireless telephony. (p), 812 ; (d), 821.
Nielson, J. F.
  Address to Scottish Students' Section. 280.
  Improvement of power factor. (d), 901.
Norris, A. G. Drive of power station auxiliaries. (d), 861.
Norway, M. L. Kristiansen appointed Local Hon. Secretary for. 596.
Notes, Institution. [*See* separate index on page 1175].

O.

Obituary notices. 1151.
Ogden, H. Electric arc welding apparatus. (d), 273.
Ogilvie, A. Domestic load building. (d), 396.
Ohtsuki, T. Shearing stress and span calculations. (p), 1079.
Oils, insulating, research on properties of. (p), 661.
——, testing of. C. Dawson, (p), 62.
Oscillograms of circuit-breaking tests. J. Rosen, (p), 458.
Overhead lines. (*See* Power Supply).

P.

Palmer, J. B., and Romero, L. Interconnection of a.c. power stations. (d), 499.
Paper-insulated cables, permissible current loading of. S. W. Melsom and E. Fawssett, (p), 517 ; (d), 579, 944.
Papers, insulating unvarnished, research on. (p), 982.
—— read, list of. 602.
Parikh, R. G., and Ganapati, S. V. Induction motors as synchronous machines. (p), 795.
Parsons, Sir Charles. Faraday medal awarded to. 595, 701, 1145.
Partridge, G. W. Problems in high-speed alternators. (d), 460.
Patents in Ireland. E. C. Handcock, (p), 144.
Paterson, H. Problems in high-speed alternators. (d), 874.
Paul Scholarship. Awarded to C. A. Wilck. 597.
Paxton, D. S. Problems in high-speed alternators. (d), 881.
Pearson, W. Address as chairman of East Midland Sub-Centre. 37.
Peck, J. S. Voltage maintenance by automatic substation. (d), 433.
Petch, H. S. Automatic and semi-automatic railway signalling. (p), 81.
Pettifor, P. G. Works production. (d), 356.
Phase advancer, chemical. T. F. Wall, (d), 119, 684.
—— advancers. G. Kapp, (p), 100 ; H. E. Yerbury, (p), 681.
—— converter. F. Creedy, (p), 313.
Physical phenomenon and application to telegraphy, etc. A. Johnsen and K. Rahbek, (p), 713.
—— properties of insulating oils, research on. (p), 661.
Pinkney, W. F. T. Domestic load building. (d), 206.
Pitt, M. Problems in high-speed alternators. (d), 470.
Pole-cores, leakage flux between. B. Hague, (p), 1072.
Porter, A. R. Current loading of paper cables. (d), 592.
Portraits of past presidents. 597.
Povey, S. E. Voltage maintenance by automatic substation. (d), 433.
Powell, D. T. Problems in high-speed alternators. (d), 468.
Power factor, improvement of. G. Kapp, (p), 89 ; (d), 109, 896.
—— factor: its technical and commercial aspects. H. E. Yerbury, (p), 675 ; (d), 681.
—— station. (*Also see* Power Supply).
—— station auxiliaries, drive of. L. Breach and H. Midgley, (p), 829 ; (d), 845.
—— station costs in America. B. Welbourn, (p), 33.
—— station costs ; load factor effect. A. S. Barnard, (p), 147.
—— stations and private plant. J. W. Beauchamp, (p), 734.
—— stations, interconnection of. L. Romero and J. B. Palmer, (d), 496 ; A. Tustin, (p), 176 ; W. B. Woodhouse, (p), 35.
—— stations, water turbines in. A. Tustin, (p), 174.

**POWER SUPPLY (General).**
  Alarm buzzer operated from central station. F. Tremain, (p), 20.
  Applications of electricity. J. W. Beauchamp, (p), 733 ; F. Hooper, (p), 726.
  Domestic load building. W. A. Gillott, (p), 197 ; (d), 202, 392, 890.
  Electric power in iron and steel industries. W. P. Richmond, (p), 158 ; H. West, (p), 152.
  Electricity as applied to mines. J. C. Stewart, (p), 167.
  Hydro-electric power supply. A. Tustin, (p), 174.
  Progress on North-East Coast. W. P. Richmond, (p), 158.
  Relationship of undertakings to public. W. B. Woodhouse, (p), 36.
  Statistics for Canada and U.S.A. B. Welbourn, (p), 32.
  Suggestions for hot-water supply. F. Tremain, (p), 19.

**POWER SUPPLY (General)** (*continued*).
  Water power from tides. F. Tremain, (p), 20.
  —— power schemes in Ireland. E. C. Handcock, (p), 141.

**POWER SUPPLY (Distribution and Transmission).**
  Electric line calculations. W. T. J. Atkins, (p), 1044.
  Maintenance of voltage on d.c. distribution system by automatic substation. P. J. Robinson, (p), 417; (d), 425, 704.
  Overhead aluminium lines, tests on. (p), 1013.
  —— copper lines, tests on. (p), 997.
  —— distribution line, economics of. F. Gill, (p), 793.
  —— galvanized steel lines, tests on. (p), 1026.
  —— steel-cored aluminium lines, tests on. (p), 1041.
  Pressures, high transmission. B. Welbourn, (p), 34.
  Progress in distribution and transmission. W. B. Woodhouse, (p), 36.
  Shearing stress and span calculations. T. Ohtsuki, (p), 1079.
  Transmission by 100 000-volt cables. A. M. Taylor, (p), 220; (d), 239, 382.
  —— problems: electric line calculations. W. T. J. Atkins, (p), 1044.
  Use of old telephone lines. F. Tremain, (p), 20.

Preece, G. G. L.
  Improvement of power factor. (d), 131
  Voltage maintenance by automatic substation. (d), 706.
Premiums, presentation of. 65.
Prescott, J. C. Improvement of power factor. (d), 127.
Presidents, past, portraits of. 597.
Press, A. Stationary waves on open-ended solenoids. (p), 405.
Pressboard for insulating purposes, report on. (p), 486.
Pressure. (*See* Voltage).
Prince of Wales, H.R.H. The. Message from, at Annual Dinner, 1923. 400, 597.
Proceedings of the Institution. 64, 293, 403, 610, 700, 800, 1139.
Proving house, electrical, Council's report on. 599.
Pumping in mines. J. C. Stewart, (p), 169.
Purse, F. W. Speaking at Annual General Meeting, 1923. 1150.
Pyne, A. P. Works production. (d), 893.

R.

Radiation and atomic bombardment. A. G. Warren, (p), 950.
Radiography of materials. A. G. Warren, (p), 949.
Radio-telegraphy and telephony. (*See* Telegraphy and Telephony).
Rahbek, K., and Johnsen, A. A physical phenomenon and its applications to telephony, etc. (p), 713.
Railway electrification. (*See* Traction, Electric).
—— signalling, automatic and semi-automatic. H. S. Petch, (p), 81.
Raphael, F. C. Co-operation of architect and electrical engineer. (d), 740.
Ratcliff, H. A.
  Current loading of paper cables. (d), 590.
  Voltage maintenance by automatic substation. (d), 704.
Rate-fixing department of works. G. H. Nelson, (p), 343.
Rawlings, W. R. Domestic load building. (d), 204.
Rawll, R. H. Underground transmission at 100 000 volts. (d), 251.
Raworth, J. E. Presentation of bust of S. P. Thompson. 1147.
Rayner, E. H.
  Direct-reading thermionic voltmeter. (d), 304.
  Intensity of received radio signals. (d), 511.
Read, J. C. Steam turbine blading. (p), 1109.
Regenerative braking with d.c. traction. M. G. Say and H. G. Frampton, (p), 863.
Registration of electrical contractors. 599; A. S. Barnard, (p), 147; J. W. Beauchamp, (p), 735.
Regulations, Electricity, Council's report on. 599.
Relays, application of revolving magnetic drum to. N. W. McLachlan, (p), 903; (d), 926.
——, economics of design of. F. Gill, (p), 794.
—— for automatic substation. P. J. Robinson, (p), 423.
——, telegraphic, electro-adhesion applied to. A. Johnsen and K. Rahbek, (p), 721.
Reminiscences of early days. F. Tremain, (p), 16.
Repeaters, telephone. F. Gill, (p), 5.
Report of Council for 1922–23. 594.
Representation of Institution on other bodies. 603.
Research Association, Electrical, Council's report on. 600.
—— in Ireland. E. C. Handcock, (p), 144.
—— on current loading of paper cables. (p), 517; (d), 579.
—— on insulating unvarnished papers. (p), 982.
—— on overhead aluminium lines. (p), 1013.
—— on overhead copper lines. (p), 997.
—— on overhead galvanized steel lines. (p), 1026.
—— on pressboard for insulating purposes. (p), 486.
—— on properties of insulating oils. (p), 661.
—— on steel-cored aluminium lines. (p), 1041.
—— on vulcanized fibre. (p), 964.
Resonant vibrations of telephone receiver diaphragms. J. T. MacGregor-Morris and E. Mallett, (p), 1134.
Rettie, C.
  Drive of power station auxiliaries. (d), 854.
  Improvement of power factor. (d), 127.
Richardson, H. W. Works production. (d), 354.
Richmond, W. P. Address as chairman of Tees-side Sub-Centre. 157.
Riley, T. N. Current loading of paper cables. (d), 581.
Robertson, A. P.
  Drive of power station auxiliaries. (d), 861.
  Problems in high-speed alternators. (d), 470.
  Underground transmission at 100 000 volts. (d), 383.
  Voltage maintenance by automatic substation. (d), 710.
Robertson, A. T.
  Variable-speed a.c. motors. (d), 333.
  Voltage maintenance by automatic substation. (d), 432.
Robertson, D., and Frome, N. F. Electrical timing device. (p), 49.
Robinson, J. Local conditions and radio direction-finding. (d), 191.
Robinson, L. L. Domestic load building. (d), 202.
Robinson, M. H. Obituary notice. 1156.
Robinson, P. J.
  Drive of power station auxiliaries. (d), 851.
  Maintenance of voltage on d.c. distribution system by automatic substation. (p), 417; (d), 428, 430, 432, 434, 437, 708, 712.
Robinson, R. Works production. (d), 895.
Rogers, G.
  Underground transmission at 100 000 volts. (d), 250.
  Voltage maintenance by automatic substation. (d), 436.
Rogers, W. E. Improvement of power factor. (d), 110.
Romero, L. Improvement of power factor. (d), 132.
Romero, L., and Palmer, J. B. Interconnection of a.c. power stations. (d), 499.
Rosen, A. Current loading of paper cables. (d), 585.
Rosen, J. Problems in high-speed alternators. (p), 439; (d), 465, 471, 476, 872, 876, 882, 885, 889.
Rosling, P. Current loading of paper cables. (d), 584.
Ross, T. W. Voltage maintenance by automatic substation. (d), 427, 432.

Ross, W.
  Drive of power station auxiliaries. (d), 860.
  Problems in high-speed alternators. (d), 470.
Russell, A.
  Current loading of paper cables. (d), 580.
  Local conditions and radio direction-finding. (d), 195.
  Speaking on liquidation of old Institution. 1150.
Rye, A. N. Domestic load building. (d), 204.

S.

Salomons Scholarship. Awarded to A. H. Maggs. 597.
Say, M. G., and Frampton, H. G. Compound characteristic in regenerative braking with d.c. traction. (p), 863.
Sayers, F. M., and Sayers, H. M. Iron welding arc. (p), 266.
Sayers, H. M. Electric arc welding apparatus. (d), 271.
Sayers, H. M., and Sayers, F. M. Iron welding arc. (p), 266.
Scholarships, award of. 597.
—— in connection with War Memorial Fund. 1144.
Schools. (*See* Education).
Schuster, L. W. Problems in high-speed alternators. (d), 882.
*Science Abstracts*, Council's report on. 598.
Secretaries, Local Hon., abroad, appointment of. 596.
Seddon, E.
  Domestic load building. (d), 393.
  Problems in high-speed alternators. (d), 469.
  Voltage maintenance by automatic substation. (d), 711.
Selvey, W. M.
  Improvement of power factor. (d), 111.
  Problems in high-speed alternators. (d), 459.
  Speaking at Annual General Meeting, 1923. 1150.
  Voltage maintenance by automatic substation. (d), 426.
Sharp, C. Electric arc welding apparatus. (d), 269.
Sharp, S. Obituary notice. 1156.
Shaughnessy, E. H.
  Direction-finding in steel ships. (d), 1059.
  Intensity of received radio signals. (d), 513.
  Revolving magnetic drum for relays, etc. (d), 928.
  Transoceanic wireless telephony. (d), 821.
Shaw, J. H. Problems in high-speed alternators. (d), 464.
Shearer, A. G. Domestic load building. (d), 207.
Shearing stress, effect of, on span calculations. T. Ohtsuki, (p), 1079.
Shepherd, H. Co-operation of architect and electrical engineer. (d), 741.
Shepherd, J. Problems in high-speed alternators. (d), 464.
Ships, electric power on. J. F. Nielson, (p), 280.
——, steel, wireless direction-finding in. C. E. Horton, (p), 1049; (d), 1056.
Short-circuit, turbo-alternators under. J. Rosen, (p), 456.
Showrooms and supply undertakings. W. A. Gillott, (p), 202.
Shuttleworth, N. Theory of a.c. generation by triodes. (p), 1121.
Signalling, railway, automatic and semi-automatic. H. S. Petch, (p), 81.
Sills, G. F.
  Problems in high-speed alternators. (d), 878.
  Voltage maintenance by automatic substation. (d), 705.
Siphon recorders, application of magnetic drum to. N. W. McLachlan, (p), 903; (d), 926.
Skinner, W. R. T. Current loading of paper cables. (d), 589.
Smith, Roger T.
  Speaking at Annual General Meeting, 1923. 1149.
  Vote of thanks to J. S. Highfield for services as president. 65.
Smith, S. B. Local conditions and radio direction-finding. (d), 195.
Smith, S. P.
  Improvement of power factor. (d), 109.
  Problems in high-speed alternators. (d), 458.
  Variable-speed a.c. motors. (d), 327.
Smith-Rose, R. L. Direction-finding in steel ships. (d), 1057.
Smith-Rose, R. L., and Barfield, R. H. Local conditions and direction-finding installations. (p), 179; (d), 195.
Smout, D. T. Electric arc welding apparatus. (d), 274.
Snell, Sir John. Vote of thanks to F. Gill for presidential address. 66.
Société Française des Electriciens, letter from. 65.
Solenoids, open-ended, stationary waves on. A. Press, (p), 405.
Sound-wave energy. J. A. Fleming, (p), 614.
Sparks, C. P. Underground transmission at 100 000 volts. (d), 239.
Specifications, drawing up of. J. F. Nielson, (p), 282.
Spectrum with electronic bombardment. A. G. Warren, (p), 949.
Spurr, R. D. Voltage maintenance by automatic substation. (d), 431.
Standard apparatus and architects. J. W. Beauchamp, (p), 735.
—— apparatus for steel industry. H. West, (p), 156.
Standards Association (B.E.S.A.), Council's report on. 600.
Steam turbine blading. J. C. Read, (p), 1109.
—— versus electric drive of power station auxiliaries. L. Breach and H. Midgley, (p), 830.
Steel, constitution of, and properties of permanent magnets. E. A. Watson, (p), 641.
——, galvanized, overhead wires, tests on. (p), 1026.
—— industry, electric power in. W. P. Richmond, (p), 158; H. West, (p), 152.
Steel-cored aluminium overhead wires, tests on. (p), 1041.
Stevenson, A. F. Underground transmission at 100 000 volts. (d), 383.
Stewart, J. C. Electricity as applied to mines. (p), 167.
Stewart, J. E.
  Domestic load building. (d), 890.
  Improvement of power factor. (d), 898.
Stirling, W. Wind-driven generators. (p), 1096.
Stoney, G. Problems in high-speed alternators. (d), 876.
Storage, thermal. F. Tremain, (p), 19.
Stubbs, A. Drive of power station auxiliaries. (d), 854.
Students. (*Also see* Education).
—— and engineering economics. F. Gill, (p), 2.
Students' difficulties, in early days. F. Tremain, (p), 16.
—— Sections, Council's report on. 597.
Subscriptions for 1924, announcement of reduction in. 1149.
Substation, automatic, and maintenance of voltage on d.c. distribution system. P. J. Robinson, (p), 417; (d), 425, 704.
Suckling-Baron, A. I. Obituary notice. 1156.
Supply, power. (*See* Power Supply).
Sutton, C. Problems in high-speed alternators. (d), 884.
Swift, G. E. Voltage maintenance by automatic substation (d), 434.
Swinton, A. A. C. Revolving magnetic drum for relays, etc. (d), 926.
Switchgear for automatic substation. P. J. Robinson, (p), 418.
—— for iron and steel works. H. West, (p), 156.
—— for power station auxiliaries. L. Breach and H. Midgley, (p), 835.
—— for variable-speed a.c. motors. F. Creedy, (p), 317.
——, mining. J. C. Stewart, (p), 167.

T.

Tariffs, construction of. W. A. Gillott, (p), 197.
——, equitable. W. B. Woodhouse, (p), 36.

Tariffs for domestic hot-water supply. F. Tremain, (p), 19.
—— for electricity supply. J. W. Beauchamp, (p), 730.
—— for low power factors. G. Kapp, (p), 105.
—— on kVA basis. H. E. Yerbury, (p), 677.
Tavernor, H. P. Domestic load building. (d), 214.
Taylor, A. M.
Current loading of paper cables. (d), 592.
Problems in high-speed alternators. (d), 886.
Transmission by underground cables at 100 000/150 000 volts. (p), 220; (d), 244, 249, 251, 383, 388.
Taylor, H. W. Problems in high-speed alternators. (d), 462.
Taylor, J. E.
Intensity of received radio signals. (d), 513.
Local conditions and radio direction-finding. (d), 192.
Teago, F. J.
Drive of power station auxiliaries. (d), 856.
Improvement of power factor. (d), 125.
Stator field of 3-phase motor. (p), 1087.

**TELEGRAPHY AND TELEPHONY.**

Apparatus for location of submarine cables and faults. F. B. Young and W. Jevons, (p), 822.
Application of revolving magnetic drum to relays, etc. N. W. McLachlan, (p), 903; (d), 926.
—— of direct-reading thermionic voltmeter. E. B. Moullin, (p), 295; (d), 304.
Automatic telephone exchanges, list of. F. G. C. Baldwin, (p), 28.
Broadcasting. B. Welbourn, (p), 31.
Design of radio towers: wind pressure assumptions. C. F. Elwell, (p), 407; (d), 412.
Dielectric losses at wireless frequencies, bridge method for. M. D. Hart, (p), 697.
Directional wireless telegraphy in aircraft. C. K. Chandler, (p), 803.
Electro-adhesion applied to telegraphy, telephony, etc. A. Johnsen and K. Rahbek, (p), 713.
Field strength of Horsea wireless station. E. B. Moullin, (p), 67; (d), 308.
Inductances for high-frequency circuits. C. L. Fortescue, (p), 933; (d), 939.
Jubilee of Eastern Telegraph Co. J. F. Nielson, (p), 280.
Local conditions and direction-finding installations. R. L. Smith-Rose and R. H. Barfield, (p), 179; (d), 191.
Measurement of received signals. J. Hollingworth, (p), 501; (d), 510.
Problems in telephony. J. A. Fleming, (p), 613.
—— in radio-telephony. J. A. Fleming, (p), 635.
Resonant vibrations of telephone receiver diaphragms. J. T. MacGregor-Morris and E. Mallett, (p), 1134.
Stationary waves on open-ended solenoids. A. Press, (p), 405.
Telegraphy and telephony, early. F. Tremain, (p), 17.
Telephone, loud-speaking, electro-adhesion applied to. A. Johnsen and K. Rahbek, (p), 724.
—— progress in United Kingdom. F. G. C. Baldwin, (p), 24.
—— statistics of U.S.A. F. G. C. Baldwin, (p), 25; F. Gill, (p), 11; B. Welbourn, (p), 31.
Telephones, installing of, in buildings. J. Johnson, (d), 745.
Telephonic repeaters and long-distance telephony. J. A. Cooper, (p), 75.
Telephony and ventilation. F. Hooper, (p), 727.
—— over long distances. F. Gill, (p), 2.
Theory of a.c. generation by triodes. N. Shuttleworth, (p), 1121.
Thermionic telephone repeater. J. A. Fleming, (p), 628.

**TELEGRAPHY AND TELEPHONY** (*continued*).
Transoceanic wireless telephony. H. W. Nichols, (p), 812; (d), 820.
Wireless direction-finding in steel ships. C. E. Horton, (p), 1049; (d), 1056.
—— telephonic communication with New York. F. Gill, (d), 612.
—— telephony. E. C. Handcock, (p), 141.

Temperature measurement with Einthoven galvanometer. F. Adcock and E. H. Wells, (p), 1115.
—— rise. (*See* Heating).
Testing in early days. F. Tremain, (p), 17.
—— of materials. C. Dawson, (p), 59.
Tests, circuit-breaking, on alternators. J. Rosen, (p), 455.
—— on aluminium for overhead lines. (p), 1013.
—— on copper for overhead lines. (p), 997.
—— on galvanized steel for overhead lines. (p), 1026.
—— on overhead steel-cored aluminium lines. (p), 1041.
—— on pressboard. (p), 486.
—— on unvarnished insulating papers, directions for. (p), 982.
—— on vulcanized fibre. (p), 964.
Therapy, deep, h.t. generation for. C. H. Holbeach, (p), 369.
Thomas, E. Voltage maintenance by automatic substation. (d), 707.
Thomas, J. H. Interconnection of a.c. power stations. (d), 498.
Thompson, Mrs. Presentation of portrait of S. P. Thompson. 1146.
Thompson, S. P. Presentation of bust, library and portrait of. 1146.
Thomson, Elihu. Speaking on Silvanus Thompson. 1147.
Thomson, J. S. Drive of power station auxiliaries. (d), 860.
Thornton, W. M.
Problems in high-speed alternators. (d), 461.
Variable-speed a.c. motors. (d), 333.
Thorrowgood, W. J. Domestic load building. (d), 205.
Tidal power. F. Tremain, (p), 20; A. Tustin, (p), 176.
Tilley, H. B. Revolving magnetic drum for relays, etc. (d), 928.
Timing device, electrical. D. Robertson and N. F. Frome, (p), 49.
Tobler, A. Obituary notice. 1157.
Toppin, W. A. Domestic load building. (d), 215.
Towers, radio, and wind pressure. C. F. Elwell, (p), 407; (d), 412.
Townend, R. Works production. (d), 360.
Townley, J. W. J.
Current loading of paper cables. (d), 588.
Improvement of power factor. (d), 120.
Problems in high-speed alternators. (d), 473.
Voltage maintenance by automatic substation. (d), 429.

**TRACTION, ELECTRIC.**
Compound characteristic in regenerative braking. M. G. Say and H. G. Frampton, (p), 863.
Electric battery vehicle. H. E. Dance, (p), 1100.
Electrification of Chicago, Milwaukee and St. Paul Railroad. B. Welbourn, (p), 800.
Gas-lighted trains. A. S. Barnard, (p), 145.
Locomotives, electric, experiences with. W. P. Richmond, (p), 159.
Railway electrification, economic aspect of. A. S. Hampton, (p), 149.
—— signalling. H. S. Petch, (p), 81.
Traction motors. (*See* Motors, Electric).

Trade depression, causes of. W. P. Richmond, (p), 157.
Training. (*Also see* Education).

Training in technical schools, Council's report on. 599.
Trains. (*See* Traction, Electric).
Transfers. 294, 612, 701, 802, 1143, 1148.
Transformer for deep therapy. C. H. Holbeach, (p), 369.
—— for radiography. A. G. Warren, (p), 959.
—— for welding. J. Caldwell, (p), 263.
—— oil. (*See* Oils).
Transmission, power. [*See* Power Supply (Distribution and Transmission)].
—— problems of telephone lines. J. A. Fleming, (p), 623.
Tremain, F.
  Address as chairman of Western Centre. 16.
  Co-operation of architect and electrical engineer. (d), 737.
  Domestic load building. (d), 890.
  Works production. (d), 354.
Triodes. (*See* Telegraphy and Telephony).
Trost, O. Radio tower design and wind pressure. (d), 413.
Trouton, F. T. Obituary notice. 1157.
Turbine, steam, and power station auxiliaries. L. Breach and H. Midgley, (p), 829.
——, steam, blading. J. C. Read, (p), 1109.
——, water. A. Tustin, (p), 175.
Turbo-generator. (*See* Generators, Electric).
Turnbull, C.
  Current loading of paper cables. (d), 586.
  Variable-speed a.c. motors. (d), 333.
  Works production. (d), 894.
Turnbull, R. T. Obituary notice. 1158.
Turner, L. B. Transoceanic wireless telephony. (d), 820.
Tustin, A. Hydro-electric power supply. (p), 174.
Twiss, G. V. Underground transmission at 100 000 volts. (d), 249.

U.

Ullett, J. W. Obituary notice. 1158.

V.

Valve, wireless. (*See* Telegraphy and Telephony).
Varnishes, testing of. C. Dawson, (p), 63.
Vehicle, electric battery. H. E. Dance, (p), 1100.
Ventilation and architects. F. Hooper, (p), 727.
—— in mines. J. C. Stewart, (p), 172.
—— of turbo-alternators. J. Rosen, (p), 447; (d), 467, 472.
Vibration in squirrel-cage motors. F. T. Chapman, (p), 39.
Vibrations, resonant, of telephone receiver diaphragms. J. T. MacGregor-Morris and E. Mallett, (p), 1134.
Voltage excess on submarine cables. F. B. Young and W. Jevons, (p), 825.
—— maintenance by automatic substation. P. J. Robinson, (p), 417; (d), 425, 704.
—— regulation with 100 000-volt cables. A. M. Taylor, (p), 229.
——, high, generation for deep therapy. C. H. Holbeach, (p), 369.
——, high transmission, in America. B. Welbourn, (p), 34.
Voltmeter. (*See* Instruments).
Vulcanized fibre, directions for research on. (p), 964.

W.

Walker, Miles. Improvement of power factor. (d), 134, 902.
Wall, T. F.
  Improvement of power factor. (d), 119, 128.
  Power factor, aspects of. (d), 684.
Wallis-Jones, R. J.
  Co-operation of architect and electrical engineer. (d), 739.
  Electric arc welding apparatus. (d), 270.
  Speaking at Annual General Meeting, 1923. 1150.
War Memorial, unveiling of. 595.
—— Memorial Fund scholarships. 1144.
—— memorials, functions of. A. S. Barnard, (p), 148.
—— Thanksgiving Education Research Fund. 597.
Ward, P. Domestic load building. (d), 208.
Wardale, W. T. Power factor. (d), 687.
Warr, J. W. Underground transmission at 100 000 volts. (d), 387.
Warren, A. G. X-ray examination of materials. (p), 949.
Water heating by electricity. J. W. Beauchamp, (p), 733; A. G. Shearer, (d), 207.
——, hot, domestic supply of. F. Tremain, (p), 19.
—— power. (*See* Power Supply (General)].
Watson, E. A. Permanent magnets, properties and constitution of. (p), 641.
Watson, R. H. Domestic load building. (d), 213.
Watson, S. J. Improvement of power factor. (d), 131.
Watts, H. W. Improvement of power factor. (d), 124.
Waves, stationary, on open-ended solenoids. A. Press, (p), 405.
Waygood, O. C.
  Domestic load building. (d), 211.
  Drive of power station auxiliaries. (d), 855.
Webb, G. R. Obituary notice. 1158.
Wedmore, E. B.
  Current loading of paper cables. (d), 583.
  Electric arc welding apparatus. (d), 271.
Welbourn, B.
  Address as chairman of Liverpool Sub-Centre. 31.
  Electrification of Chicago, Milwaukee and St. Paul Railroad. (p), 800.
  Voltage maintenance by automatic substation. (d), 425, 704.
Welding apparatus, electric arc. J. Caldwell, (p), 253; (d), 268.
—— arc, iron. F. M. Sayers and H. M. Sayers, (p), 266.
——, electric. H. West, (p), 153.
Wells, E. H., and Adcock, F. Temperature measurement with Einthoven galvanometer. (p), 1115.
West, H.
  Address as chairman of Sheffield Sub-Centre. 152.
  Power factor. (d), 681.
Whysall, F. H.
  Improvement of power factor. (d), 900.
  Problems in high-speed alternators. (d), 468.
Wilck, C. A. Paul Scholarship awarded to. 597.
Wilkinson, H. D. Improvement of power factor. (d), 116.
Wilkinson, H. T. Obituary notice. 1159.
Williams, E. T.
  Current loading of paper cables. (d), 584.
  Improvement of power factor. (d), 110.
Williams, J. H. Voltage maintenance by automatic substation. (d), 433, 706.
Williams, J. R. Power factor. (d), 687.
Wilmshurst, T. P. Problems in high-speed alternators. (d), 885.
Wilson, A. S. Domestic load building. (d), 212.
Wind pressure and radio tower design. C. F. Elwell, (p), 407; (d), 412.
Wind-driven generators. W. Stirling, (p), 1096.
Winding, electric, in mines. J. C. Stewart, (p), 172.
—— of variable-speed a.c. motors. F. Creedy, (p), 310.
Windings, a.c., demonstrating M.M F. of. R. D. Archibald, (p), 376.
——, armature, distribution factor of. B. Hague and S. Neville, (d), 398.

Windings, armature, theory of M.M.F. of. A. E. Clayton, (p), 749.
——, effect of, on stator field of 3-phase motor. F. J. Teago, (p), 1087.
Wing, S. P. Radio tower design and wind pressure. (d), 414.
Wireless Section Committee, nominations for. **1144.**
—— Section, Council's report on. 596.
—— telegraphy and telephony. (*See* Telegraphy and Telephony).
Wires. (*See* Cables and Conductors).
Wiring contractors, registration of. 599; A. S. Barnard, (p), 147; J. W. Beauchamp, (p), 735.
—— electric. A. S. Barnard, (p), 145.
—— electric, and architects. J. W. Beauchamp, (p), 734.
—— Rules and grading. J. W. Beauchamp, (p), 735.
—— Rules, Council's report on. 598.
—— systems, early, failures of. A. H. Dykes, (d), 736.
Woodhouse, W. B.
  Address as chairman of North Midland Centre. 35.
  Current loading of paper cables. (d), 588.
  Domestic load building. (d), 215.
  Drive of power station auxiliaries. (d), 845.
Woodhouse, W. B.
  Improvement of power factor. (d), 110.
  Variable-speed a.c. motors. (d), 330.
Wordingham, C. H. Address to London Students' Section. 277.
Works. (*Also see* Manufacturing).
—— production. G. H. Nelson, (p), 338; (d), 352, 893.
Wright, G. M. Local conditions and radio direction-finding. (d), 193.

X.

X-ray examination of materials. A. G. Warren, (p), 949.
—— generation for deep therapy. C. H. Holbeach, (p), 369.

Y.

Yerbury, H. E.
  Improvement of power factor. (d), 119.
  Power factor: its technical and commercial aspects. (p), 675; (d), 687, 690.
Young, F. B., and Jevons, W. Apparatus for location of submarine cables and faults. (p), 822.
Young, H. T. Domestic load building. (d), 205.

# INDEX TO "INSTITUTION NOTES," NOS. 35-40.

1923.

Adcock, F., and Wells, E. H. Students' Premium awarded to. (21).
Aircraft (Anti-) Battalion, Royal Engineers (T.A.). (1).
American I.E.E. and visiting members. (5).
Annales des Postes, Télégraphes et Téléphones. (6).
Appointments Board, Electrical. (9).
Atkins, W. T. J. Students' Premium awarded to. (21).
Ayrton Premium. Awarded to F. Creedy. (18).

Banks, R. E. David Hughes Scholarship awarded to. (21).
Booth, H. C., and Melsom, S. W. Kelvin Premium awarded to. (18).
Breach, L., and Midgley, H. Premium awarded to. (18).
British plant, specification of, Council's resolution on. (9).

Caldwell, J. Paris Premium awarded to. (18).
Certificates and diplomas, national, in electrical engineering. (18).
Chapman, F. T. Premium awarded to. (18).
Colleges approved for national diplomas in electrical engineering. (18).
Committees, constitution of, 1922–23. (2).
Conversazione, Annual, announcement of date of. (9), (13).
Cooper's Hill War Memorial Medal and Premium. (21).
Council for 1923–24: result of ballot. (17).
Creedy, F. Ayrton Premium awarded to. (18).

Dance, H. E. Students' Premium awarded to. (21).
Definitions, photometric, of International Illumination Commission. (14).
Devonshire, Sir James. Elected Vice-President. (17).
Diplomas and certificates, national, in electrical engineering. (18).
Donaldson, J. M. Elected Member of Council. (17).
Dover, A. T. Premium awarded to. (18).
Dunn, G. Appointed Local Hon. Secretary for U.S.A. (5).

Economics of engineering design. (10).
Education Fund, War Thanksgiving: grant to R. H. Holmes. (9).
Engineering design, economics of. (10).
Engineers, Royal (T.A.), Anti-Aircraft Battalion. (1).
——, Royal, examination results. (1), (19).
——, Royal, Old Comrades' Association. (10).
English-speaking Nations Committee and visiting members. (10).
Examination results, Associate Membership. October 1922: (1), (9), (13); February 1923: (13); April 1923: (19).

Fahie Premium. Awarded to H. W. Nichols. (18).
Faraday Medal. Awarded to Sir C. A. Parsons. (9).
Fleming, J. A. Elected Honorary Member. (1).
Fortescue, C. L. Wireless Premium awarded to. (18).

Hollingworth, J. Wireless Premium awarded to. (18).
Holmes, R. H. Grant from War Thanksgiving Fund. (9).
Honorary Member. J. A. Fleming elected. (1).
Hopkinson (John) Premium. Awarded to J. Rosen. (18).
Hughes (David) Scholarships awarded to R. E. Banks and R. MacWhirter. (21).

Illumination Committee of Great Britain, report of, for 1922. (14).
Index, Ten-Year, publication of. (17), (21).
India, Institution of Engineers: award of premium to A. L. Stanton. (13).
Informal Meetings, proceedings of. (5), (14).
Institution of Engineers (India): award of premium to A. L. Stanton. (13).
—— Premium. Awarded to G. Kapp. (18).
—— register, removal from. (10).
—— representatives on other bodies. (3).
International Conference on e.h.t. power transmission. (5), (9).
—— Consulting Committee for telephone communication. (13).

*Journal*, short papers for. (18).

Kapp, G. Institution Premium awarded to. (18).
Kelvin Premium. Awarded to S. W. Melsom and H. C. Booth. (18).
Kerr, W. T. Name removed from Institution register. (10).
Kristiansen, M. L. Appointed Local Hon. Secretary for Norway. (5).

Lane, J. F. Salomons Scholarship awarded to. (21).
Library, Lending, accessions to. (8), (15), (22).
——, Reference, accessions to. (10), (16), (19), (22).
Lines, overhead. (*See* Transmission).
Linton, J. Salomons Scholarship awarded to. (21).
List of members, 1923. (17).
Local Hon. Secretaries abroad, new, appointed. (5).

McLachlan, N. W. Wireless Premium awarded to. (18).
MacWhirter, R. David Hughes Scholarship awarded to. (21).
Medal, Cooper's Hill War Memorial. (21).
——, Faraday. Awarded to Sir C. A. Parsons. (9).
Meeting, Annual General, announcement of. (13).
——, Ordinary, 12th April, 1923, announcement of. (9).
——, Summer, 1923, announcement of. (5).
Meetings, Informal, proceedings of. (5), (14).
——, Ordinary, time of. (21).
Melsom, S. W. Elected Member of Council. (17).
Melsom, S. W., and Booth, H. C. Kelvin Premium awarded to. (18).
Member, Honorary, J. A. Fleming elected. (1).
Members, list of. (17).
——, visiting, from Dominions and Colonies. (10).
—— visiting U.S.A., privileges for. (5).
Memorial (War), Cooper's Hill, Medal and Premium. (21).
—— (War) Fund Scholarships established. (9).
Midgley, H., and Breach, L. Premium awarded to. (18).
Moullin, E. B. Wireless Premium awarded to. (18).

National diplomas in electrical engineering. (18).
Nichols, H. W. Fahie Premium awarded to. (18).
Norway, M. L. Kristiansen appointed Local Hon Secretary for. (5).

Papers, short, for *Journal*. (18).
Paris Premium. Awarded to J. Caldwell. (18).
Parsons, Sir C. A. Faraday Medal awarded to. (9).
Partridge, G. W. Elected Member of Council. (17).
Photometric definitions of International Illumination Commission. (15).
Plant, British, specification of, Council's resolution on. (9).
Portrait of Sir Francis Ronalds, presentation of. (18).
Power transmission, e.h.t., I.E.E. representatives at International Conference on. (9).
—— transmission, e.h.t., proceedings of International Conference on. (5).
Premium, Cooper's Hill War Memorial. (21).
Premiums, award of, for 1922–23. (18), (21).
Purves, T. F. Elected Member of Council. (17).

Read, J. C. Students' Premium awarded to. (21).
Register, Institution, removal from. (10).
Representatives of Institution on other bodies. (3).
Research Association, British Electrical, progress reports of. (6), (21).
—— Fund, War Thanksgiving: grant to R. H. Holmes. (9).
Robinson, P. J. Premium awarded to. (18).
Ronalds, Sir Francis, presentation of portrait of. (18).
Rosen, J. John Hopkinson Premium awarded to. (18).
Rosling, P. Elected Member of Council. (17).
Russell, A. Elected President. (17).

Salomons Scholarships awarded to F. J. Lane and J. Linton. (21).
Scholarships, award of, for 1923. (21).
——, War Memorial Fund, established. (9).
Secretaries, Local Hon. (*See* Local Hon. Secretaries).
Signals, Royal Corps of: examination results. (13).
Specification of British plant, Council resolution on. (9).
Stanton, A. L. Institution of Engineers (India) premium awarded to. (13).
Stirling, W. Students' Premium awarded to. (21).
Students' Premiums, award of, for 1922–23. (21).
Subscriptions, annual, from 1st January, 1924. (17).

Télégraphes et Téléphones, Annales des Postes. (6).
Telephone communication, International Consulting Committee for. (13).
Ten-Year Index, publication of. (17).
Thornton, W. M. Elected Member of Council. (17).
Transmission, e.h.t., I.E.E. representatives at International Conference on. (9).
——, e.h.t., proceedings of International Conference on. (5).
Tuckett, P. D. Elected Honorary Treasurer. (17).

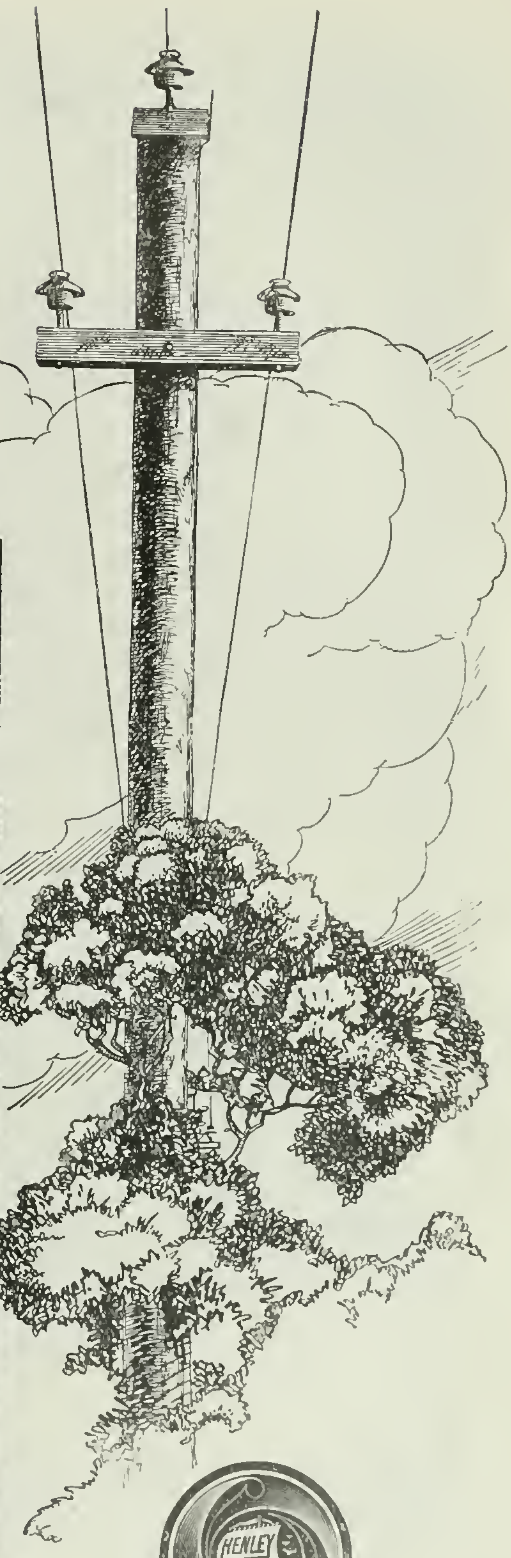
United States, G. Dunn appointed Local Hon. Secretary for. (5).
—— States, members visiting, privileges for. (5).

Visiting members. (*See* Members).

War Memorial, Cooper's Hill, Medal and Premium. (21).
—— Memorial Fund Scholarships established. (9).
—— Thanksgiving Fund; grant to R. H. Holmes. (9).
Wells, E. H., and Adcock, F. A. Students' Premium awarded to. (21).
Wireless Section Premiums, award of, for 1922-23. (18).

*Printed in Great Britain by*
UNWIN BROTHERS, LIMITED, THE GRESHAM PRESS, LONDON AND WOKING

# Experto Crede



## Overhead Transmission

SOMETIMES the line is a short one running across a yard, sometimes it covers miles of rough, hilly country. Sometimes the conditions are abnormal, often they are unprecedented. Whatever type it is, whether short or long, wood pole, tubular steel pole, lattice steel towers, or concrete poles or towers, we can probably help you.

We do not offer help in any arbitrary spirit, but having great experience in the erection of overhead lines of every type, our engineers are in a position to suggest the best method of procedure—the best type of line.

We offer their experience to you without obligation. A Henley engineer will call to see you if you will fix your own time and date.

This is part of the service Henleys offer you.

*"Experto Crede." Trust one who has had experience.*

**HENLEY**

W. T. HENLEY'S TELEGRAPH WORKS
CO., LTD.,
BLOMFIELD STREET, LONDON, E.C. 2.

TRA MARK

10,000 H.P. Water Driven Alternator

High Grade Electrical Machinery

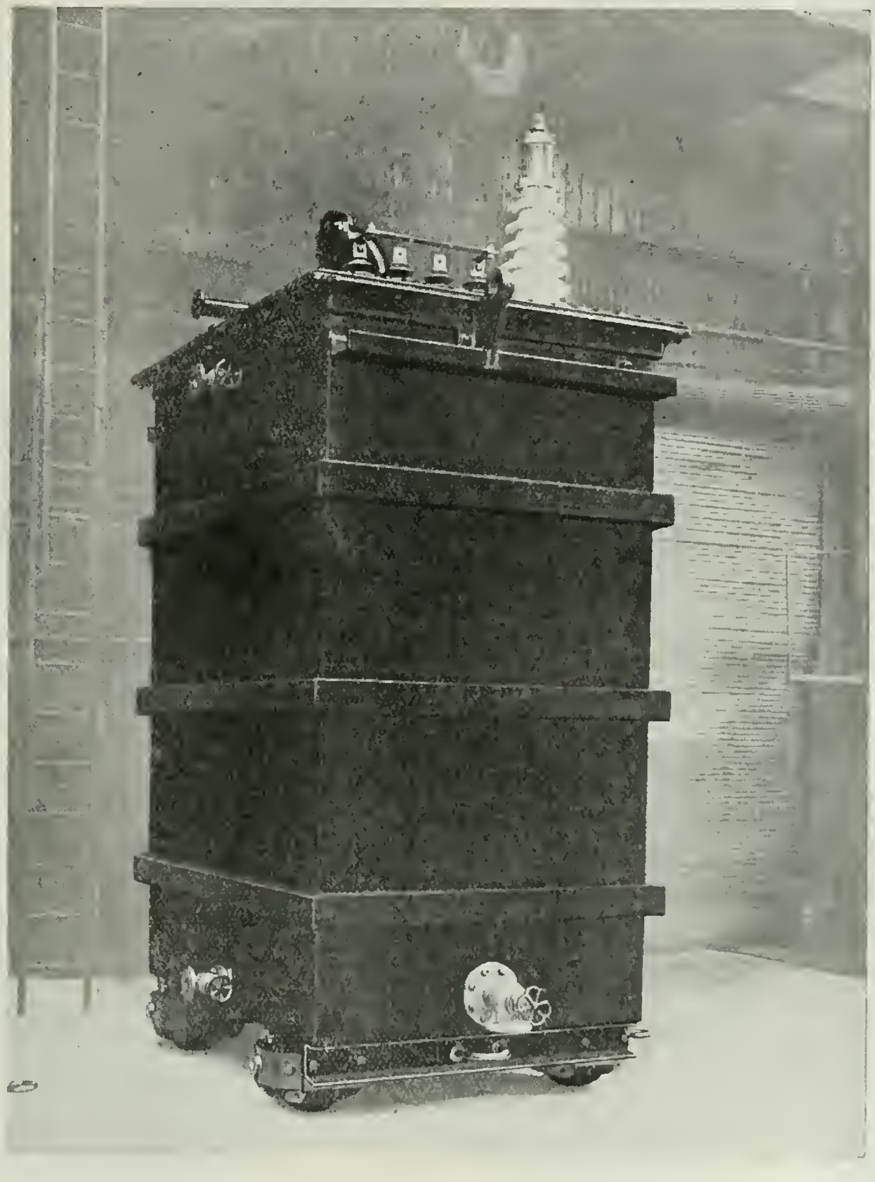
THE illustrations presented afford excellent examples of the high grade products of our Works, and indicate the capacity of the Company to manufacture plant of the largest magnitude.

The picture shows a group of 10,000 H.P. Water Driven Alternators under construction in our Preston Works, while in the foreground is a completed machine. These alternators are being supplied to the Midi Railway of France in connection with their electrification scheme.

The
ENGLISH ELECTRIC
Company Limited.
WORKS:- BRADFORD, COVENTRY, PRESTON, RUGBY, STAFFORD.
HEAD OFFICE:-
Queen's House, Kingsway, London, W.C.2.

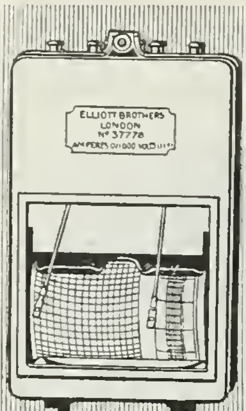
FERRANTI

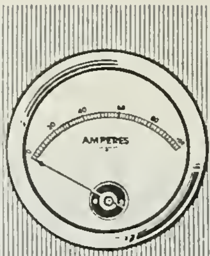
TRANSFORMERS

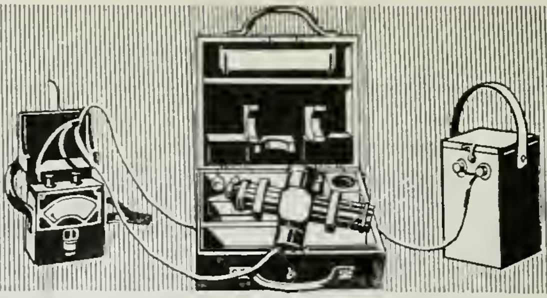


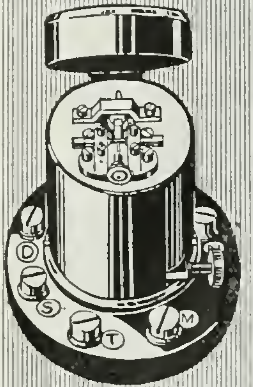
A 4,000 K.V.A. TRANSFORMER
TO WORK ON 110,000 VOLTS.

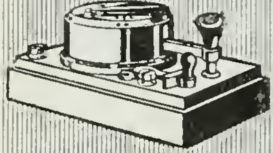
**FERRANTI LIMITED, HOLLINWOOD, LANCASHIRE.**

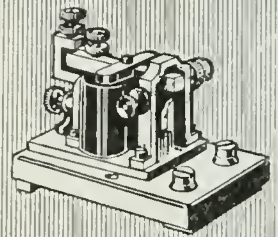


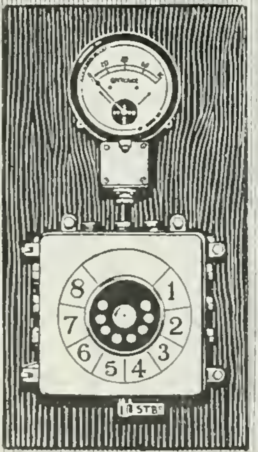










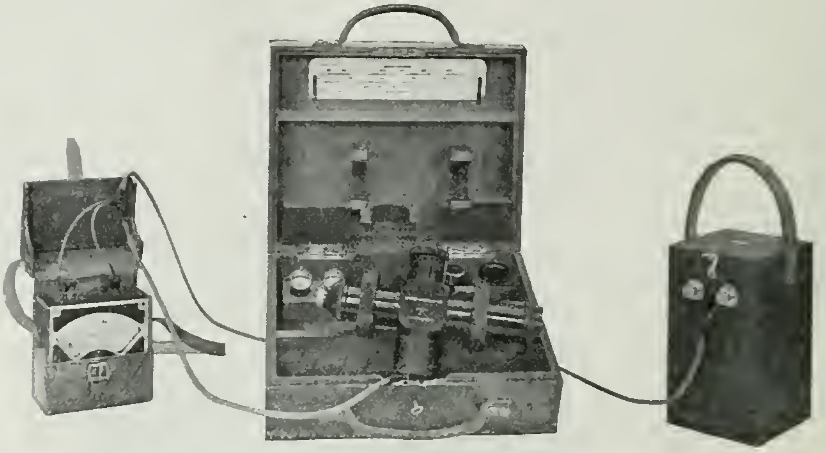


# SIEMENS

## OPTICAL PYROMETER

**For temperatures above 600°. Cent.**

PATENT No. 17927/13.



This pyrometer has been specially designed for measuring very high temperatures, particularly in cases where it is impracticable to employ thermo-electrical pyrometers.

PRINCIPLE OF THE INSTRUMENT.—The heated object whose temperature is to be measured is observed through a telescope and its **brightness** is compared with that of a standardised electric lamp, fitted inside the telescope. The temperature of the lamp varies with the current passed through it. This is measured by an ammeter and the corresponding temperature is read on a specially calibrated scale.

The brightness of the lamp is controlled by two variable resistances mounted on the telescope. These are circular in form and are adjusted by means of the two milled rings which can be seen in the illustration. On viewing the heated object through the telescope, the image of the lamp filament is seen superimposed on it. By adjusting the variable resistances the brightness of the filament is increased until it equals that of the heated object, and the filament will then appear to melt into the background. If the current is further increased, the filament will appear bright on a comparatively dull background. The human eye is very sensitive to changes in light intensity, and the point at which the filament disappears is quite definite and will be found to be the same (within very small limits of personal error) by different observers.

*Descriptive pamphlet on application*

**SIEMENS**
BROTHERS
& Co LIMITED,
WOOLWICH, LONDON, S.E.18.
*ESTABLISHED 1858.*

IN ASSOCIATION WITH

**ELLIOTT**
BROTHERS
(LONDON) LIMITED,
CENTURY WORKS, LEWISHAM, S.E.13.
*ESTABLISHED 1800.*

Manufacturers of D.C.

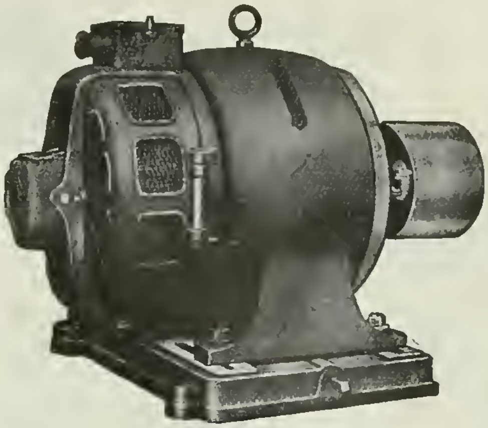
**DYNAMOS & MOTORS**

Up to 150 B.H.P.

**Built in accordance with the new B.E.S.A. Specification No. 168/1923 with its conservative rating and heavy overload capacity.**

SUPPLIERS TO:

H.M. Admiralty, War Office, Air Board, :: India Office, Crown Agents, :: H.M.O.W. G.P.O., Royal Mint, and other Government Departments at home and abroad.



"Magnet," Manchester. 741 Openshaw
"Orders," Cannon, London. 5370 City.

Electromotors Limited

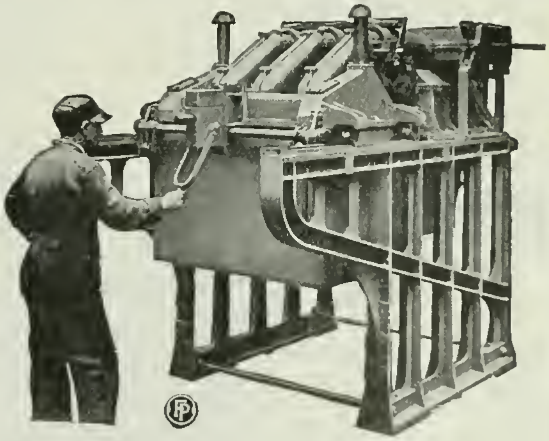
**OPENSHAW:**
Manchester. England
London. 49 Queen Victoria Street. E.C

---

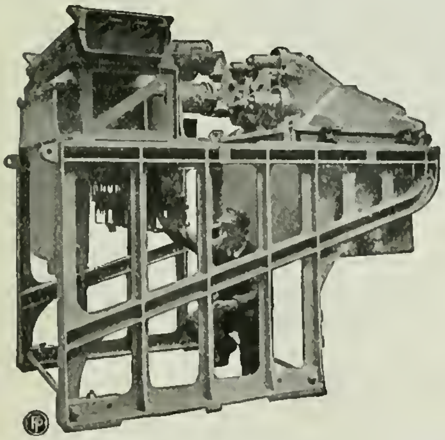
**IRONCLAD SWITCHGEAR**
**TYPE H**

**Direct or Remote Mechanically Operated**
**Electrically Operated by Simple Solenoid**
1,500 Amps., 6,600 Volts. 1,500 Amps., 12,000 Volts.
600 Amps., 22,000 Volts. 300 Amps., 44,000 Volts.

**Three-Phase Rupturing Capacity 500,000 K.V.A.**



SHOWING DIRECT OPERATION OF THE CIRCUIT BREAKER.



SHOWING THE COMPLETE ACCESSIBILITY OF THE TRANSFORMERS.

**VERMIN, OIL VAPOUR, DUST AND MOISTURE PROOF**

*Send for List No. 174, A1*

All Instrument and Protective Transformers Oil-Immersed

Automatic tripping with any type of discriminative protective gear without the use of relays, auxiliary supply circuits or auxiliary switches.

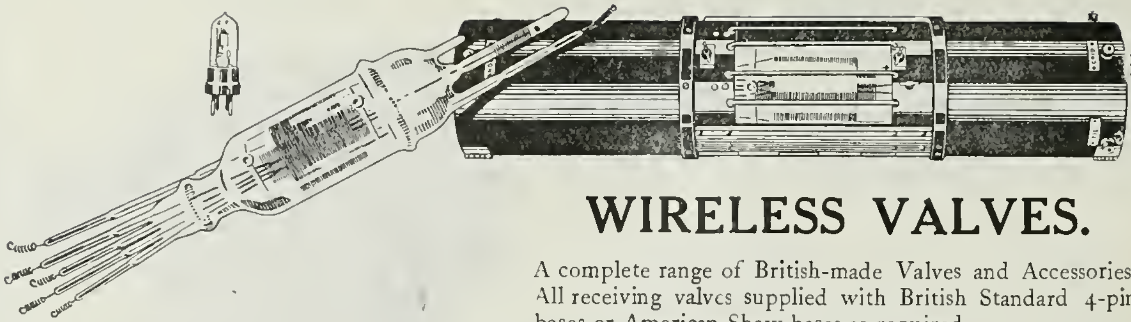
**FERGUSON, PAILIN LTD.**

*THE SWITCHGEAR SPECIALISTS*

**HIGHER OPENSHAW** **MANCHESTER**

'Phone: Openshaw 329
'Grams: Tension, Manchester

D.R.K.53



## WIRELESS VALVES.

A complete range of British-made Valves and Accessories. All receiving valves supplied with British Standard 4-pin bases or American Shaw bases as required.

**Types "Ora" and "R" Valves.** General purpose valves for good reception, using 4-volt batteries.

**Type "L.F." Valves.** Special low filament current consumption valves for reception, using 2-volt accumulators or suitable primary batteries.

**Type "P.A." Valves.** Specially designed valves for use with loud speakers, giving good volume without distortion.

**Type "O" and "U" Valves.** Power rectifying and transmitting valves in glass or silica for outputs from 5 watts to kilowatts.

**Grid Leaks and Anode Resistances.** Mullard Patent, ensuring constant value under all climatic conditions.

**Valve Bases and Accessories.** Made in best moulded material for use with Mullard Valves.

*Write to-day for fully Illustrated Catalogues.*

Mullard
Radio Valve Co. Ltd.

45 Nightingale Lane, Balham, S.W.12

Telephone: Battersea 1068
Telegrams: Radiovalve, Wandscom, London

Codes: A.B.C. (6th Edition), Bentley's.

Contractors to H.M. Admiralty, War Office, Royal Air Force, and Post Office.

E.P.S.

Trade Mark
Radio Mullard Valve

43

LEW

## RUBBER INSULATED WIRES AND CABLES

SILK, COTTON and ENAMEL INSULATED WIRES & STRIPS

HIGH RESISTANCE WIRES and STRIPS

FLEXIBLE LIGHTING and TELEPHONE CORDS

BELL WIRES

Manufactured by
**The London Electric Wire Co. & Smiths Ltd.**
Playhouse Yard, Golden Lane, London, E.C.1

Telegrams: Electric, London.
Telephones: Clerkenwell 1388, 1389, 1390

THE
## FOUNDATION
Co. Ltd.

WINDSOR HOUSE
KINGSWAY
LONDON, W.C.2

CONTRACTORS
FOR AND
SPECIALISTS
IN

POWER SCHEMES
TRAMWAYS
RAILWAYS
Etc.

**Mica, Leatheroid, Vulcanized Fibre**

EMPIRE CLOTH AND TAPE

**Bakelite Sheets, Tubes, Spools, etc.**

for Oil-immersed Apparatus and Transformers.

**BAKELITE RESIN, VARNISH & MOULDING POWDER.**

**EBONITE** AND ALL INSULATING MATERIAL FOR ELECTRICAL MANUFACTURERS

**ATTWATER AND SONS,**

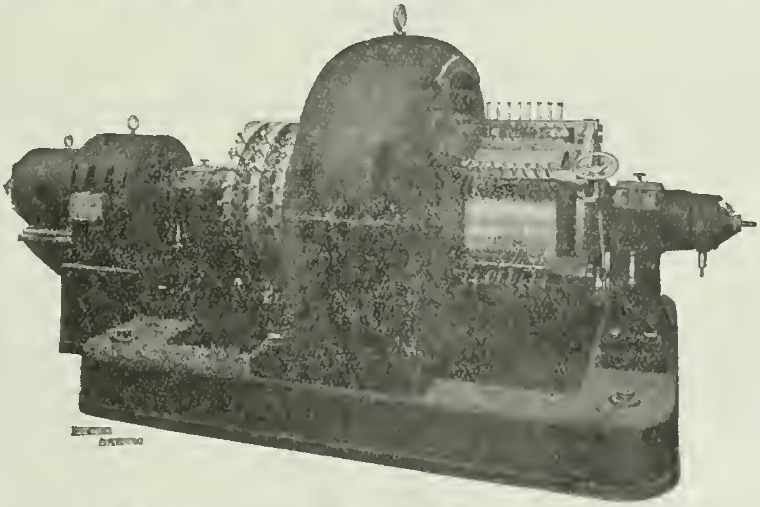
ESTABLISHED 1868,

**PRESTON, ENGLAND.**

*Contractors to the British, American, French and Italian War Offices and Admiralties.*

---

**CONVERTERS** PATENT SELF-SYNCHRONIZING



**THE ELECTRIC CONSTRUCTION CO. LTD.**

Head Office

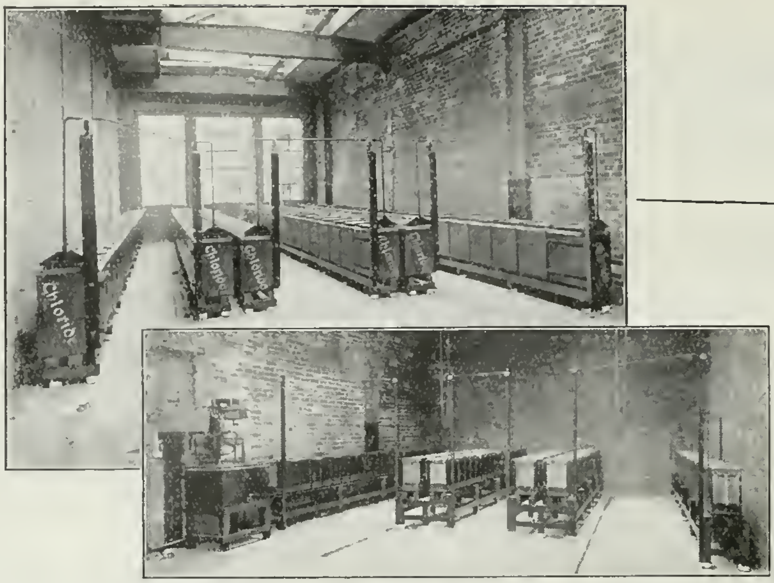
INGERSOLL HOUSE, 9 KINGSWAY, LONDON, W.C. 2

WORKS

WOLVERHAMPTON

Telegrams :—
"Concordance" Estrand London.

Telegrams :—
"Electric" Wolverhampton.



120 T.R.W. 8
CELLS.
CAPACITY
1200 a.h.

120 H.R.G. 5
CELLS.
CAPACITY
300 a.h.

TWO STORAGE BATTERIES RECENTLY COMPLETED AT

## BARTON POWER STATION, MANCHESTER.

**THE Chloride ELECTRICAL STORAGE COMPANY LIMITED.**

**CLIFTON JUNCTION,**
**Nr. Manchester.**

**57 Victoria Street,**
**London, S.W.1**

---

## WATER POWER

BRITISH DESIGN. BRITISH MANUFACTURE
*TESTED* TURBINES.

SLUICE GEAR. PELTON WHEELS. TURBINES. SLUICE VALVES. PIPE LINES. OIL PRESSURE GOVERNORS.

*Catalogue and Prices on application to*

**HAY MARYON & Co. LTD.**
WATER POWER ENGINEERS AND CONTRACTORS
14 BRIDE LANE, LONDON, E.C.4.
**Works: HAY MARYON WORKS (STROUD) LTD., STROUD, GLOS.**
Telephone: Cent 1814.
Telegrams:
"Hamabrila, Fleet, Lond."

---

## *Inspection and Insurance of Electrical Plant* —

REAL SERVICE. BREAKDOWNS MINIMISED.
REPAIR COSTS STABILISED.
FIRST-CLASS REPAIRS ENSURED.

PLANT also examined and tested for purchasers by our own Engineer-Surveyors, and reports supplied.

MAKERS' GUARANTEE RISKS COVERED.

Over 140 Engineer-Surveyors resident in principal towns.

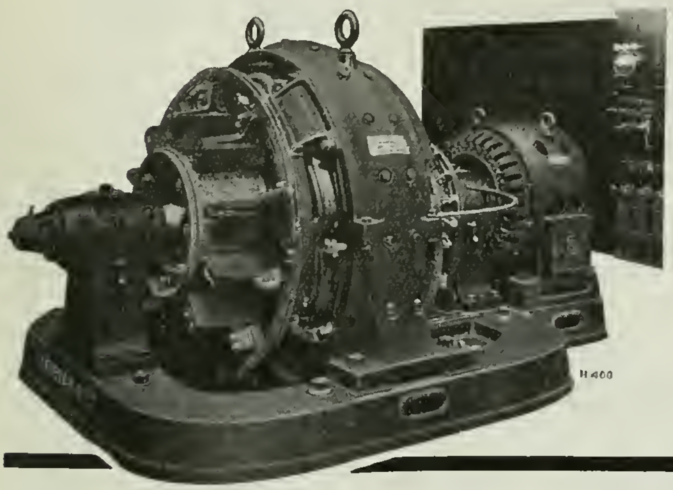
**BRITISH ENGINE, BOILER & ELECTRICAL INSURANCE CO., LTD.**

**Manchester, 24 Fennel Street**
**London, 56 Kingsway, W.C. 2**
**Glasgow, 40 St. Vincent Place**

and numerous other towns in the United Kingdom

ROTARY CONVERTERS

*Rotaries supplied to or on order for :—*
Manchester Corporation.
Liverpool Corporation.
Cardiff Corporation.
Bath Corporation.
Barnes U.D.C.
North Metropolitan Electric Power Supply Co.
&c., &c.



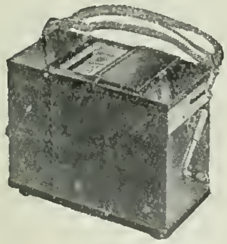
**Mather & Platt, Ltd.**
**Electrical & Hydraulic Engineers**
**Park Works, MANCHESTER.**
**14 Great Smith Street, London, S.W. 1**
Branch offices, Agents or Representatives in most countries.

*Special features :—*
High efficiency at all loads.
High power factor at all loads.
Patent Self Synchronizing System.
Long Life.
Simplicity of operation.
Low starting current.

---

RECORD

ELECTRICAL MEASURING INSTRUMENTS
OF THE HIGHEST QUALITY



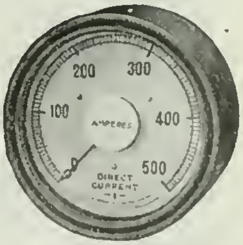
RECORD OHMMETER.

Comprising various types of Ammeters and Voltmeters for A.C. and D.C.

The "Record" Ohmmeter and Generator for insulation testing.

"Cirscale" Switchboard instruments.

Miniature "Cirscale" Multi-range Test Set for "Wireless" measurements.



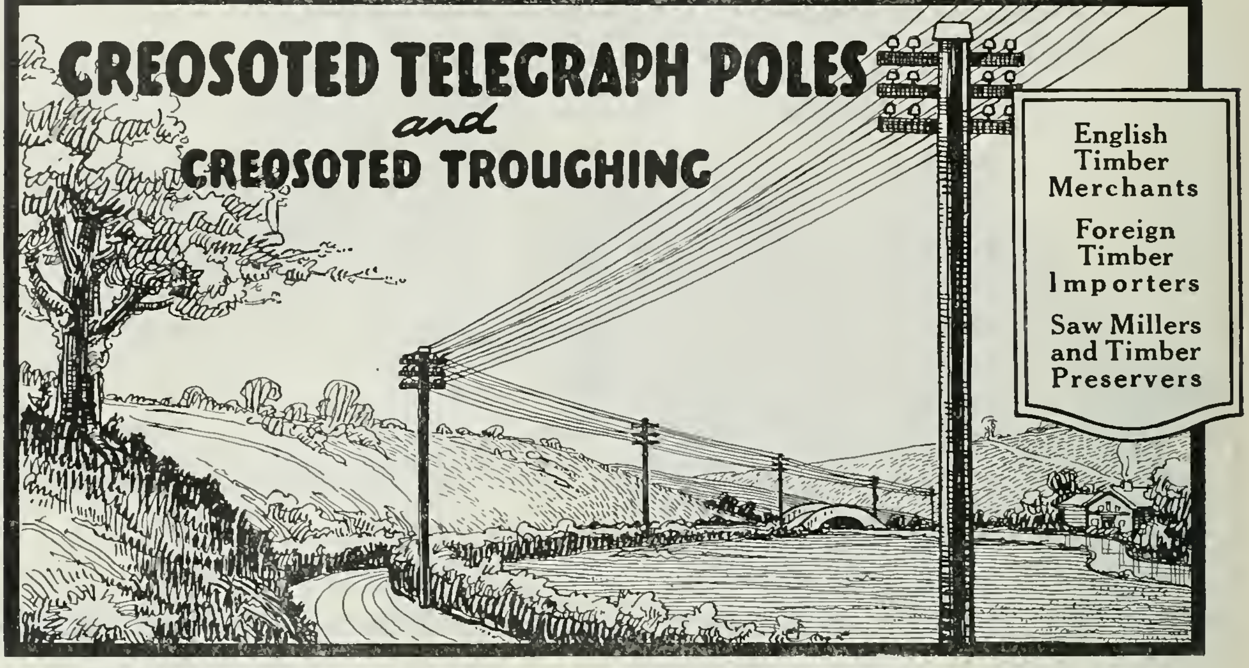
"CIRSCALE."

THE RECORD ELECTRICAL CO., LTD.
BROADHEATH, MANCHESTER.

*Telephone : Altrincham 164.* *Telegrams : "Infusion Altrincham."*

**BURT, BOULTON & HAYWOOD LTD.**
SALISBURY HOUSE, LONDON WALL, LONDON, E.C.2
Pole Yards at: SOUTHAMPTON (Totton), NEWPORT (Mon.), LONDON (Silvertown)
TELEPHONE: LONDON WALL 7569—72.

CONTRACTORS TO
GENERAL POST OFICE
Etc.



BELLING ELECTRIC FIRES

FOR

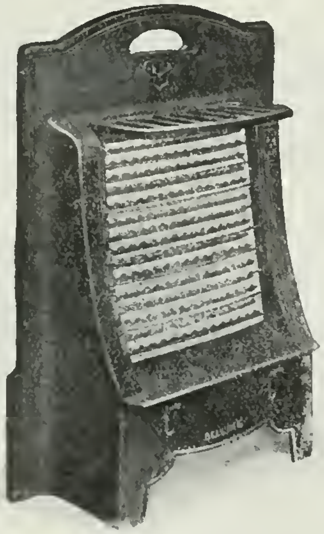
OFFICES AND FACTORIES,
HOTELS AND RESTAURANTS,
CHURCHES AND HOSPITALS,
SHIPS AND RAILWAY WORK,
SHOPS AND DOMESTIC USE, ETC.

Over 3,000 Electrical Engineers regularly buy "Belling" Fires, Cookers and other Domestic Electrical Appliances.

We have just introduced several new and interesting designs of Fires

Send for our 1923/4 Illustrated Catalogue.

**BELLING & Co.,** *Electric Heating Specialists,*
Derby Road Works, Edmonton, London, N.18.



MEDAL AWARDED ST. LOUIS, 1904

When Re-charging
ACCUMULATORS
it is important to
**have the right acid.**

**B.A.A.**
REGD

is specially prepared and tested.
Being **made from the Best**
**Brimstone and Distilled Water,**
it is the

**PUREST & BEST ACID**
**for ACCUMULATORS**

REGISTERED B A A TRADE MARK

*Sole Manufacturers :*
**F. W. BERK & CO. LTD.**
**1 Fenchurch Ave., London, E.C.**
Telephone: AVENUE 2403 (5 lines) Telegrams: "BERK, LONDON"
*Works :*
Abbey Mills Chemical Works, STRATFORD, E.
Pentrepoth Chemical Works, MORRISTON, SWANSEA

Associate

**TUDOR BATTERIES**

with your electrical storage in

1. Central Station and Power Installations.
2. Private House Lighting.
3. Train and Ship Lighting.
4. Electric Vehicles.
5. Wireless Requirements.

*Write and consult us*

*The* TUDOR ACCUMULATOR
Co. Ltd.

2 Norfolk Street, Strand, London, W.C. 2

*Telephone* - - - *Central* 3308.
*Telegrams* - - - *Subconical, Estrand, London.*
*Works* - - *Dukinfield, near Manchester.*

(ENG.P.S.45.)

*And you will get it!*

THE sample of "ARNOCO" Oil you receive and try to-day is exactly the same—in every particular—as the oil of the same grade you will order in twelve months or two years' time. Never is any variation from sample permitted. This is a feature buyers of oil for use on electrical plant very much appreciate.

We are Specialists in the preparation of oils suitable for Turbines, Transformers and Switches, Gas Engines and all Electrical Plant.

We are regular suppliers to various important Electrical undertakings in every part of the country.

Write for prices and samples of oils suitable for your particular work. On receipt of details of the kind of service for which the lubricant is intended, we shall be glad to suggest the most efficient and economical oil.

"Arnoco" REGD
LUBRICANTS

Write :—

**JAMES ARNOTT & SONS Ltd.**

*Head Office :*

**47 Pilgrim St., Newcastle-on-Tyne**

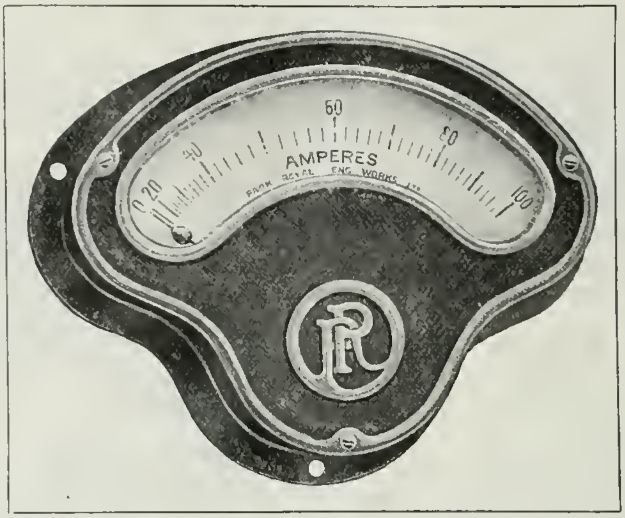
*Uniform Quality Always*

# THE BEST INSTRUMENTS

AMMETERS

and

VOLTMETERS



MOVING COIL

and

MOVING IRON

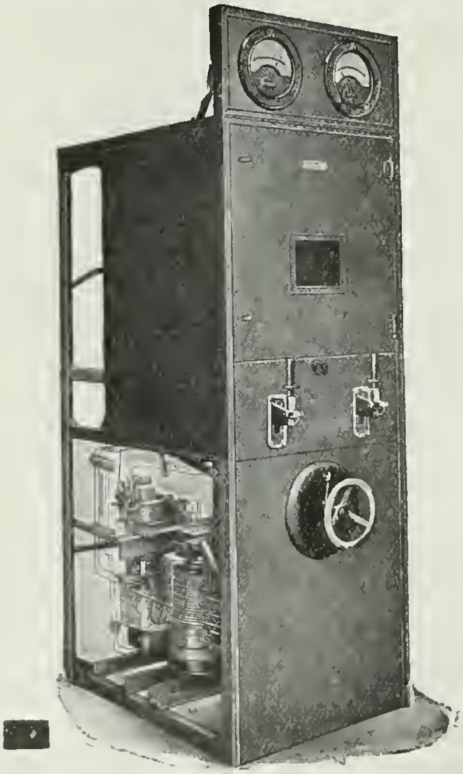
TYPES

## PARK ROYAL ENGINEERING WORKS LTD.

WILLESDEN 2223, 2224.

PARK ROYAL, LONDON, N.W. 10.

---



# *Alternating to Direct Current*

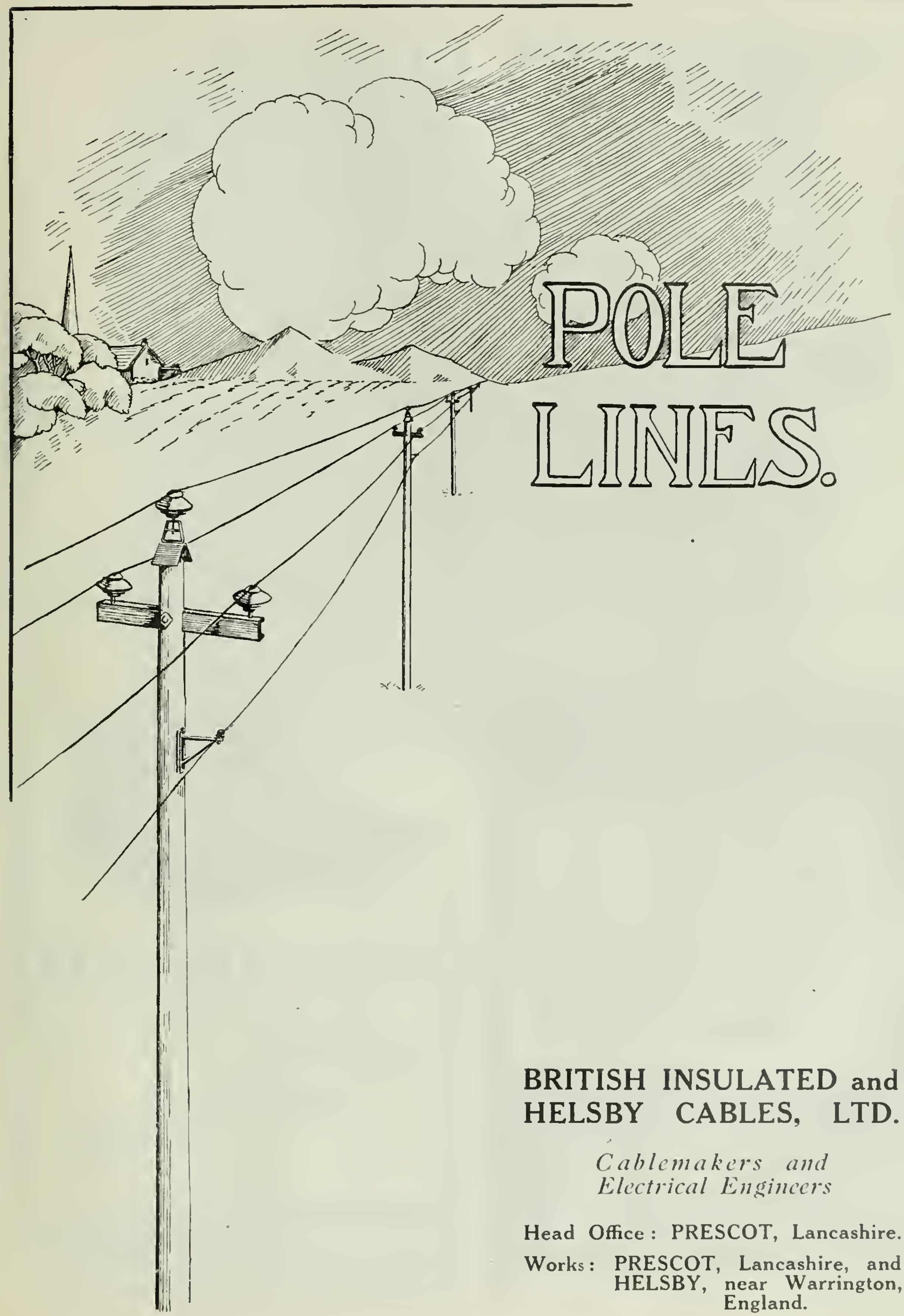
Mercury Vapour
Rectifiers ——
Simple & Reliable
of all Capacities

*Call and see the Rectifiers in our Showrooms*

## HEWITTIC ELECTRIC COMPANY, LTD.

80 York Road, KING'S CROSS, LONDON, N. 1.

Telephone : North 624 & 625. Telegrams : "Hewittic, Kincross, London."



**BRITISH INSULATED and HELSBY CABLES, LTD.**

*Cablemakers and*
*Electrical Engineers*

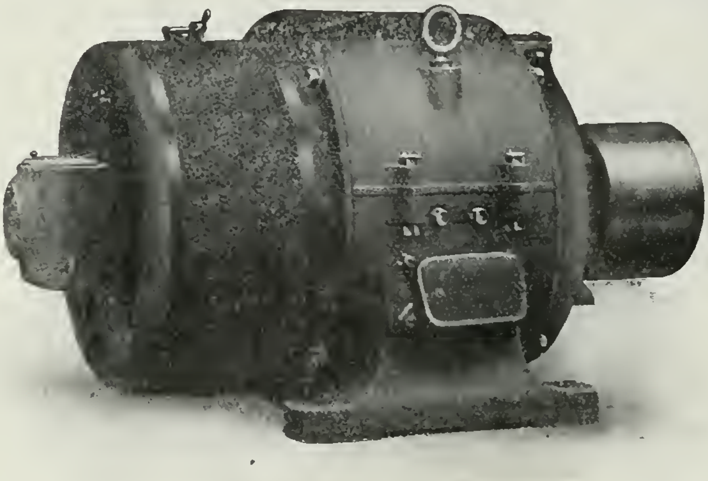
Head Office: PRESCOT, Lancashire.

Works: PRESCOT, Lancashire, and
HELSBY, near Warrington,
England.

MAWDSLEY'S LIMITED,
MANUFACTURING ELECTRICAL ENGINEERS,
DURSLEY, GLOS.

Telegrams: "ZONE, DURSLEY."
Telephone: DURSLEY 6.

SPECIALISTS
IN
DIRECT-CURRENT
DYNAMOS
AND
MOTORS



TAYLOR & CHALLEN
PRESSES.

NEW PRESSES AT WORK & ON VIEW IN OUR SHOWROOMS – FOR IMMEDIATE DELIVERY.

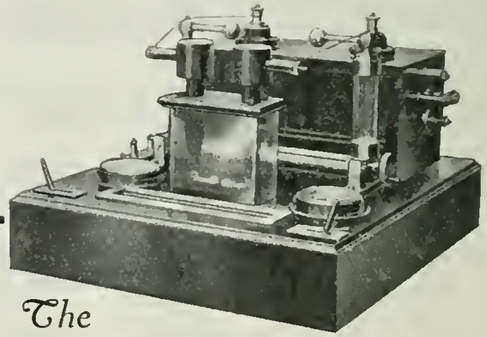
PRESSES
FOR
BLANKING & NOTCHING ARMATURE
~ PLATES & SEGMENTS ~
AND PRODUCTION OF

METER CASES, TRANSFORMER PLATES, SEAMLESS MOTOR-COVERS, CABLE ENDS, SEAMLESS LAMP REFLECTORS & LAMP FITTINGS.

SWITCHBOARD & TELEPHONE PARTS, MAGNET CUTTING AND BENDING. PRESS MOULDED INSULATORS. ETC. ETC.

PRESSES OF ALL SIZES FOR SHEET METAL WORK
SEAMLESS HOLLOWARE & ALL DIE PRESSED WARE
— COMPLETE PLANTS FOR —
COINING. MINTING. CARTRIDGE &
GUNPOWDER MANUFACTURE.

TAYLOR & CHALLEN LTD. ENGINEERS & MAKERS.
DERWENT FOUNDRY. WORKS & SHOWROOMS
TELEGRAMS DERWENT BHAM. BIRMINGHAM TELEPHONE CENTRAL 376.
LONDON OFFICE: ST STEPHEN'S HOUSE VICTORIA EMBANKMENT. S.W.1. TELEGRAMS, TAYCHAL PARL. TELEPHONE, VICTORIA 3513.

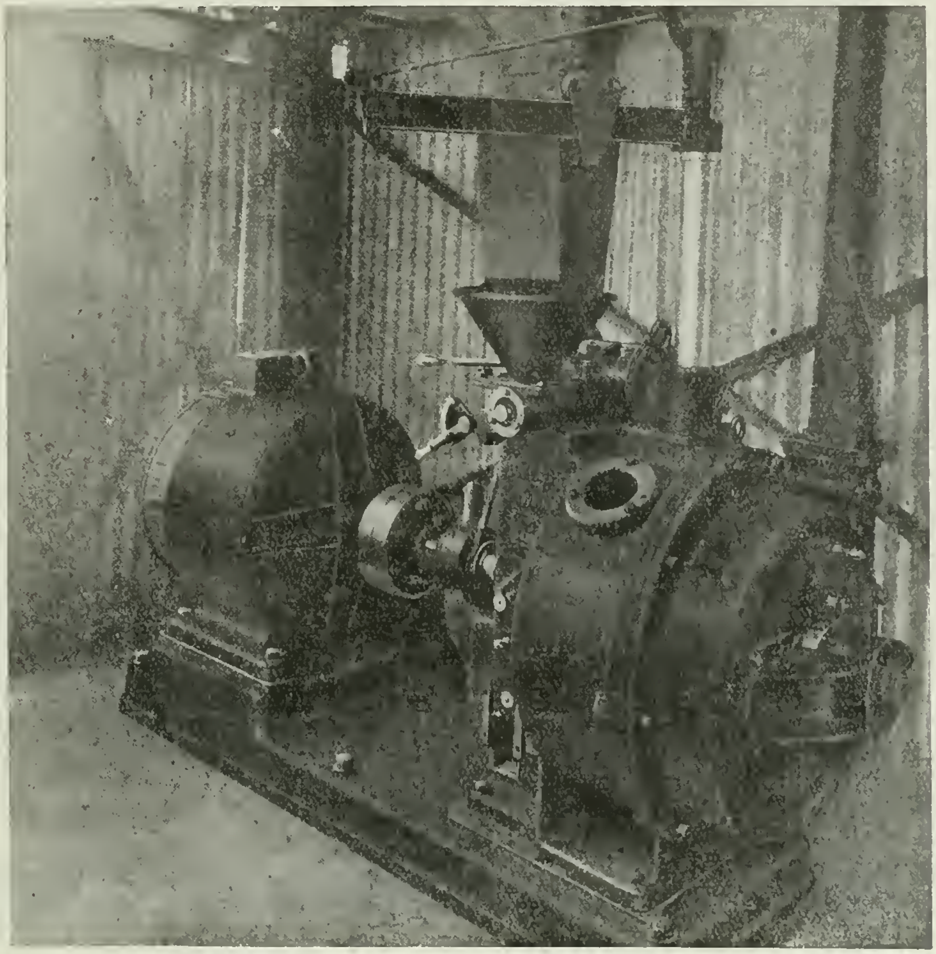


*The*
DIELECTRIMETER
*for testing the B.D.V. of Insulating Oils.*

PORTABLE,
INEXPENSIVE
& RELIABLE.

*Sole Manufacturers:*
EMPSON ELECTRICAL ENGINEERING CO. LTD.
*Albany Buildings, 47 Victoria St., London, S.W. 1*

# ALFRED HERBERT LTD., COVENTRY



View of Atritor supplying Pulverised Fuel for heating Babcock & Wilcox Boiler.

## SMOKELESS CHIMNEYS

THE smoke nuisance of industrial areas *can* be abolished. Coal properly pulverised burns with just a thin white haze coming from the chimney.

No elaborate plant is necessary.

The Atritor, a self-contained machine, separates, dries, granulates, pulverises, aerates and blows the fuel into the furnace in such a form that after it has burned no combustible matter remains in the ash.

There is little noise and no dust with the Atritor system.

The machine is automatic; the operator has only to regulate the feed and speed lever.

The Atritor eliminates the necessity of storing pulverised coal. A Babcock & Wilcox Boiler at our Edgwick Works is in regular use fired by the Atritor. The fuel is smudge containing moisture up to 25%, which is the cheapest variety of colliery slack with a thermal content as delivered of about 9,000 B.T.U. per pound. The evaporative efficiency with this low grade of fuel, which is used without preliminary drying, is

**67%**

without an economiser and without a superheater.

**THERE IS NO BLACK SMOKE.**

Demonstrations by Appointment.

Sole Concessionaires for metallurgical furnace installations.

THE WELLMAN SMITH OWEN ENG'G
CORPORATION LTD.
36/38 Kingsway, London, W.C. 2

# Reduced Prices of MAZDA GASFILLED LAMPS from Sep. 1st

1899 A

## ~~OLD PRICES~~

| ~~WATTS~~ | ~~VOLTS 100,105,110,115, 120,125,130.~~ | | ~~VOLTS 200,205,210,220,225, 230,240,250,260~~ | |
|---|---|---|---|---|
| | ~~s.~~ | ~~d.~~ | ~~s~~ | ~~d.~~ |
| ~~30~~ | ~~3~~ | ~~0~~ | — | |
| ~~40~~ | ~~3~~ | ~~0~~ | ~~3~~ | ~~6~~ |
| ~~60~~ | ~~3~~ | ~~6~~ | ~~4~~ | ~~0~~ |
| ~~75~~ | — | | — | |
| ~~100~~ | ~~6~~ | ~~0~~ | ~~6~~ | ~~0~~ |
| ~~150~~ | ~~8~~ | ~~6~~ | ~~8~~ | ~~6~~ |
| ~~200~~ | ~~10~~ | ~~6~~ | ~~10~~ | ~~6~~ |
| ~~300~~ | ~~13~~ | ~~6~~ | ~~13~~ | ~~6~~ |
| ~~500~~ | ~~17~~ | ~~0~~ | ~~17~~ | ~~0~~ |
| ~~1,000~~ | ~~21~~ | ~~0~~ | ~~21~~ | ~~0~~ |
| ~~1,500~~ | ~~30~~ | ~~0~~ | ~~27~~ | ~~6~~ |

## NEW PRICES

| WATTS | VOLTS 100,105,110,115, 120,125,130. | | VOLTS 200,205,210,220,225, 230,240,250,260 | |
|---|---|---|---|---|
| | s | d | s | d. |
| 30 | 2 | 6 | — | |
| 40 | 2 | 6 | 3 | 0 |
| 60 | 3 | 0 | 3 | 0 |
| 75 | 4 | 0 | 4 | 0 |
| 100 | 5 | 0 | 5 | 0 |
| 150 | 7 | 0 | 7 | 0 |
| 200 | 9 | 0 | 9 | 0 |
| 300 | 12 | 0 | 12 | 0 |
| 500 | 15 | 0 | 15 | 0 |
| 1,000 | 20 | 0 | 20 | 0 |
| 1,500 | 27 | 6 | 27 | 6 |

*SEND YOUR ORDER TO-DAY*

**The British Thomson-Houston Co. Ltd.**

*Office:* Crown House, Aldwych, W.C.2. *Stores:* Mazda House, 77 Upper Thames Street, E.C.4, and 5-7 Wenlock Road, N.1. *Works:* Rugby, Willesden, Coventry, Birmingham. *Branches:* Belfast, Birmingham, Cardiff, Dublin, Glasgow, Leeds, Liverpool, Middlesborough, Manchester, Newcastle, Swansea, Sheffield.

---

## THE SALESMAN AND E.D.A.

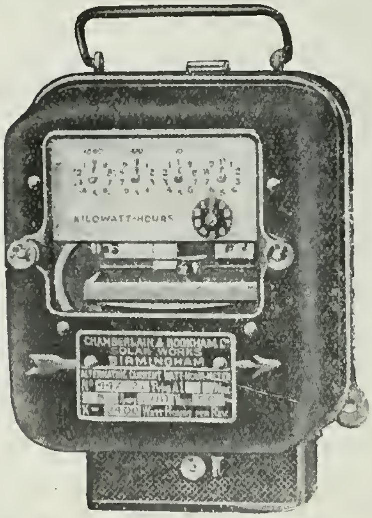
*Selling Electriciy*
involves work, goodwill, patience, endurance, knowledge and experience on the part of the representatives of Suppliers, Manufacturers, Contractors and all those engaged in the Industry.

E.D.A. believes that a free and frank interchange of opinions in the Conference room will lead to the more rapid achievement of the Salesman's object to his own immediate benefit and ultimately to the benefit of the whole Industry.

E.D.A. SALESMANSHIP CONFERENCES (London area) are held monthly at St. Bride's Institute, E.C. Programmes and season tickets will be provided on application to E.D.A., 15 Savoy Street, W.C. 2.

---

# METERS



Chamberlain & Hookham, Ltd., possess unique facilities for the manufacture and supply of Electricity Meters of every description, including D. C. Amp. Hour Meters, Tram Car Meters, Polyphase Meters, Single-phase Meters, D.C. Watt-hour Meters, Electric Vehicle Meters.

*Enquiries Invited*

**Chamberlain & Hookham Ltd**

ELECTRICITY METER MANUFACTURERS.
SOLAR WORKS, BIRMINGHAM.

*Telephone:* Central 2161. *Telegrams:* "Solar, Birmingham."

London Office & Test Room—MAGNET HOUSE, KINGSWAY, W.C. 2

*Telephone:* Regent 7050 (Ext. 9). *Telegrams:* "Solarique, Westcent, London."

**BABCOCK & WILCOX LIMITED**
ENGINEERS AND CONTRACTORS

**Patent Water-tube Steam Boilers**
**Over 16,000,000 horse-power**
Installed or on Order for **Land Work alone**

**Over 5,500,000 h.p. installed or on order for Electrical Undertakings.**

ALSO MAKERS OF EXPRESS TYPE LIGHT-WEIGHT BOILERS

CONVEYORS, ELECTRIC CRANES, AND COMPLETE BOILER-HOUSE EQUIPMENT

BABCOCK & WILCOX BOILERS SUPPLIED TO THE ROTHERHAM CORPORATION. ☛

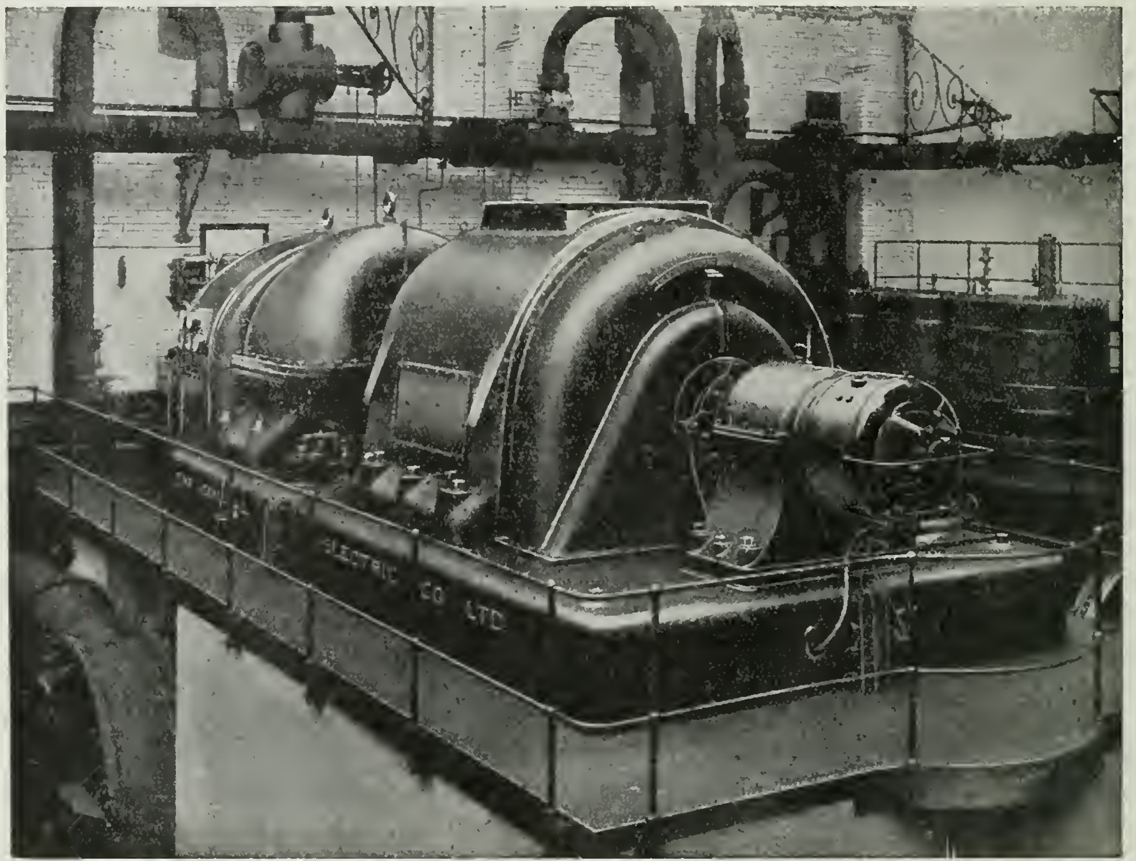
*Telegrams: "Babcock, Cent. London."* HEAD OFFICES: *Telephone Nos.: 6470 City (8 lines).*
**BABCOCK HOUSE, FARRINGDON STREET, LONDON, E.C. 4**
**Principal Works:** RENFREW, SCOTLAND. Branch Works: Dumbarton, Scotland; Oldbury, England; and in Italy, Australia and Japan

## LIST OF ADVERTISERS IN THIS ISSUE

| | PAGE |
|---|---|
| Arnott (James) and Sons, Ltd. | xi |
| Attwater and Sons | vii |
| Babcock and Wilcox, Ltd. | xvii |
| Belling and Co. | x |
| Berk (F. W.) and Co., Ltd. | xi |
| British Electrical Development Association | xvi |
| British Engine, Boiler and Electrical Insurance Co., Ltd. | viii |
| British Insulated and Helsby Cables, Ltd. | xiii |
| British Thomson-Houston Co., Ltd. | xvi |
| Burt, Boulton and Haywood, Ltd. | x |
| Chamberlain and Hookham, Ltd. | xvi |
| Chloride Electrical Storage Co., Ltd. | viii |
| Electric Construction Co., Ltd. | vii |
| Electromotors, Ltd. | v |
| Empson Electrical Engineering Co., Ltd. | xiv |
| English Electric Co., Ltd. | ii |
| Ferguson, Pailin, Ltd. | v |
| Ferranti, Ltd. | iii |
| Foundation Co., Ltd. | vi |
| General Electric Co., Ltd. | xviii |
| Hay, Maryon and Co., Ltd. | viii |
| Henley's (W.T.) Telegraph Works Co., Ltd. | i |
| Herbert (Alfred), Ltd. | xv |
| Hewittic Electric Co., Ltd. | xii |
| London Electric Wire Co. and Smiths, Ltd. | vi |
| Mather and Platt, Ltd. | ix |
| Mawdsley's, Ltd. | xiv |
| Mullard Radio Valve Co., Ltd. | vi |
| Park Royal Engineering Works, Ltd. | xii |
| Record Electrical Co., Ltd. | ix |
| Siemens Bros. and Co., Ltd. | iv |
| Taylor and Challen, Ltd. | xiv |
| Tudor Accumulator Co., Ltd. | xi |

GEC
FRASER & CHALMERS

TURBO——PLANT



6,000 K.V.A., G.E.C.—Fraser & Chalmers Turbo-Alternator Set in a London Municipal Power House. 6,000/6,600 volts, 50 cycles, 3,000 r.p.m.
This Power House also contains two 1,500 KW. G.E.C. Rotary Converters.

The association of Fraser & Chalmers Engineering Works with the G.E.C. places this Company in the position of manufacturing complete Turbo-Power Plant Units within its own organization.

TURBO-ALTERNATORS
ranging from the smallest to the largest units.
TURBO-GEARED D.C. GENERATORS.
TURBINE or ELECTRIC DRIVE
for Mills in every industry.
High, Low, Mixed-Pressure & Pass-out Types.
STEAM TURBINES.

The products of the G.E.C. and its associated factories embrace the entire mechanical and electrical equipment of power plant in practically every sphere, including:

POWDERED FUEL FIRED BOILERS.
COAL & ASH HANDLING PLANT.
A.C. and D.C. GENERATORS.
ROTARY CONVERTERS.
MOTOR GENERATORS.
SWITCHBOARDS & SWITCHGEAR.
STEAM & ELECTRIC WINDING ENGINES.
ELECTRIC HAULAGE GEAR.

THE GENERAL ELECTRIC CO., LTD.

*Head Office:* MAGNET HOUSE, KINGSWAY, LONDON, W.C. 2.
Engineering Works: WITTON WORKS, BIRMINGHAM.
Fraser & Chalmers Engineering Works, ERITH, KENT.

TK
1
I4
v.61
~~Physical &~~
~~Applied Sci.~~
~~Serials~~
ENGINEERING
…eering

Institution of Electrical
Engineers, London
Proceedings

PLEASE DO NOT REMOVE
CARDS OR SLIPS FROM THIS POCKET

UNIVERSITY OF TORONTO LIBRARY

ENGIN STORAGE